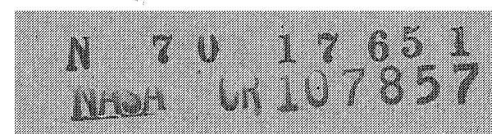


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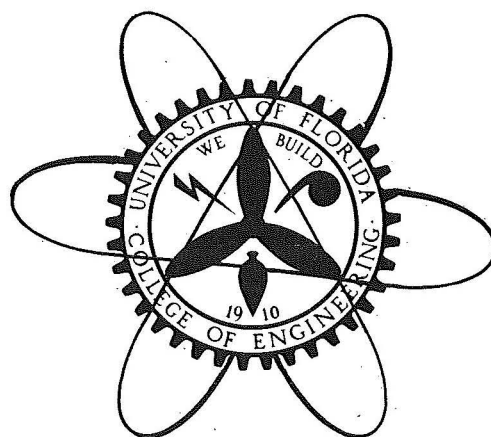
Of The Symposium On

Research On Uranium Plasmas And Their Technological Application

January 7-10, 1970

University Of Florida

Gainesville



Sponsored by

National Aeronautics and Space Administration

and

Department of Nuclear Engineering Sciences

College of Engineering

University of Florida

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SYMPOSIUM PROGRAM

January 7, 1970

WEDNESDAY MORNING

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M. J. Ohanian, Chairman
Department of Nuclear
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Symposium Program Chairman

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Air Force Office of Scientific
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SATURDAY MORNING

A tour of the NASA facilities at Cape Kennedy.

1-1 A COMPARISON OF OPEN AND CLOSED CYCLE GASEOUS
CORE REACTOR SYSTEMS

F. C. Schwenk and C. E. Franklin
Space Nuclear Propulsion Office
Washington, D. C.

The present advanced propulsion concepts being supported by the National Aeronautics and Space Administration generally lie either in the electric or nuclear fields. This paper looks only at the nuclear options for advanced propulsion systems and defines advanced nuclear propulsion, for the purposes of this paper, to be gaseous core reactors. The general characteristics of gaseous core reactors are described and a brief review is made of gas core concepts which have been previously supported by NASA. The major emphasis of the paper, however, is placed on a detailed comparison of the two prime gas core candidates; i.e., the open cycle coaxial flow system and the closed cycle nuclear light bulb system. Limiting features for each are discussed and a judgment is made as to their critical components, as well as the potential for solution.

1-2 EFFECT OF ENGINE PARAMETERS ON FUEL CONTAINMENT IN AN OPEN-CYCLE GAS-CORE REACTOR

Robert G. Ragsdale
Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio

An analysis is carried out to determine how the amount of nuclear fuel that would exist in a gaseous reactor is affected by various engine parameters. The latest results from gas-core fluid mechanics experiments and from uranium plasma composition and opacity theory are used in the analysis. The engine parameters considered are: cavity diameter, reactor pressure, engine thrust, engine specific impulse, and the ratio of hydrogen flow rate to uranium flow rate.

A number of auxiliary equations were required to obtain the final one that relates fuel mass to engine parameters. The results of two recent experiments showed that the fraction of reactor cavity volume that will be occupied by fuel \bar{V} is given by the following function of the fuel-to-propellant average density ratio, $\bar{\rho}$, and the propellant-to-fuel flow rate ratio, \bar{W} :

$$\bar{V} = (\bar{W})^{-1/3} (\bar{\rho})^{-1/6}$$

Similar equations for the uranium plasma density, ρ , and absorption coefficient, a , are written in terms of pressure and temperature:

$$\rho = (\text{const}) \frac{P}{T^{1.77}}$$

$$a = (\text{const}) \frac{P}{T^{2.4}}$$

These equations are incorporated into a recently published diffusion analysis of radiant heat transfer. The final result is an equation for the fuel mass in the engine in terms of cavity diameter, D ; engine pressure, P ; thrust, F ; specific impulse, I_{sp} ; and hydrogen-to-uranium flow rate ratio, \bar{W} . The equation is:

$$M = .14 \frac{D^{3.3} P^{.7}}{F^{.28} I^{.28} (\bar{W})^{.36}}$$

This equation is then used to examine the various engine trade-offs that are available between these parameters.

1-3 SUMMARY OF RESEARCH ON THE NUCLEAR LIGHT BULB REACTOR*

G. H. McLafferty and J. W. Clark
United Aircraft Research Laboratories
East Hartford, Connecticut

The nuclear light bulb engine is based on the transfer of energy by thermal radiation from gaseous nuclear fuel suspended in a neon vortex, through an internally cooled transparent wall, to seeded hydrogen propellant. Such an engine offers the possibility of providing values of specific impulse greater than 1500 sec, thrust-to-weight ratios greater than 1, and containment of the gaseous nuclear fuel without loss of fuel or fission products in the exhaust from the engine. In addition, it may be possible to obtain many reuses from such an engine by replenishing the spent recirculating fuel. Removal of the spent fuel and fission products from the engine would also reduce the radiation hazards during multiple-rendezvous missions.

Determination of the feasibility of a nuclear light bulb engine requires research in a number of technology areas: investigations of vortex fluid mechanics and radiant heat transfer, development and testing of thin internally cooled transparent-wall structures, investigations of radiation-induced absorption in transparent walls due to neutrons and gamma rays, and studies of overall engine characteristics (including engine start-up and engine dynamics). The research accomplished to date and the relation between the results of these investigations and the engine characteristics (such as size, specific impulse, and weight) will be discussed.

* This research was supported by the joint AEC-NASA Space Nuclear Propulsion Office under Contracts NASw-847 and SNPC-70.

1-4 THE COLLOID CORE CONCEPT -- A POSSIBLE FORERUNNER FOR THE GASEOUS CORE

Y. S. Tang, J. S. Stefanko and P. W. Dickson
Westinghouse Electric Corporation
Astronuclear Laboratory
Pittsburgh, Pennsylvania

The solid core reactor concept, representing the state-of-the-art in nuclear propulsion systems, offers a greater specific impulse, I_{sp} , than chemical propulsion systems by more than a factor of two. The gaseous core concept, on the other hand, can theoretically provide a value of I_{sp} on the order of five to nine times that of chemical systems. The feasibility of reaching such a high specific impulse, however, depends on the fuel-retention characteristics of a vortex-stabilized engine.

A concept using colloid fuel, which has the inherent advantages of easier containment and separation, was conceived by Aerospace Research Laboratory (ARL) of Wright-Patterson Air Force Base. The capability of retaining the fissionable material in the reactor cavity is enhanced in this concept through the utilization of a large density difference between the fuel-bearing material in particulate form and the propellant.

Under ARL sponsorship Westinghouse conducted a design study which included a theoretical analysis of colloid core characteristics and the evaluation of technological problem areas. A conceptual design of the ground test reactor was made for demonstrating the operation principles of this concept. The reactor uses particulate fuel with a composition $(1U-10Zr)C$. The uranium is U-233, and the fuel is fed to the cavity by hydrogen gas. The cavity, a compressed vortex chamber developed by ARL, has an L/D ratio of 0.15 in the fuel-

bearing zone. Beryllium is used as the reflector material. The reflector, as well as the other core components, is cooled by hydrogen passages contained in a titanium alloy (Ti-Al-V) pressure vessel. The engine would generate a 100,000 pound thrust with a specific impulse of $1200 \text{ lb}_f\text{-sec/lb}_m$.

A comparison was made between the colloid core reactor and a specific nuclear light-bulb engine of similar thrust, as reported by The United Technology Center of United Aircraft Corporation in 1968. The weight of the engine plus propellant is comparable for a mission time of 20 minutes.

1-5 PULSED PLASMA CORE ROCKET REACTORS

F. Winterberg
Desert Research Institute
University of Nevada System

It is shown that the two principle problems of gas core reactors, that is 1) fuel propellant separation and 2) material problems resulting from the high operating temperature, can be greatly reduced by a pulsed operation to very high temperatures by a fast growing chain reaction. An expression for the reactor economy (for the fuel burn up) is derived which shows that with increasing maximum temperature in the pulsed reactor operation the same fuel burn up is possible with a smaller fuel propellant separation. In the limiting case of temperatures above 10^7 °K, no separation is needed. This limiting case is represented by the bomb propulsion concept. For intermediate temperatures less separation is needed for the same fuel burn up. The other limiting case, that of complete separation realized in the solid core rocket reactor, can also be recovered from the general formula.

The pulsed operation will not only reduce the material problems connected with continuous operation at high temperatures but also will lead to a higher specific impulse not attainable under continuous operation.

1-6 GASEOUS FISSION CLOSED LOOP MHD GENERATOR

Arthur Sherman
Computer and Applied Sciences, Inc.
Philadelphia, Pennsylvania

For some years now research workers have been studying the problem of how to generate large amounts of electrical power efficiently and in a light weight system for use in space flight. Most detailed studies have been done assuming a conventional (although high performance) solid core nuclear reactor with turbomachinery used for the thermal to electrical energy conversion. Some thought has been given to the use of an MHD generator here, but due to the limited temperatures available from solid core reactors such a generator would be a marginal performer unless substantial amounts of non-equilibrium ionization were possible. Accordingly, research continues on non-equilibrium ionization in such generators. In any event, the system contemplated regardless of the conversion method would probably, at best, operate in the 10-25 Kg per Kw range of specific weights. An alternative to such a heavy system is the solid core nuclear rocket, and this device is presently being studied vigorously.

Another alternative is the gas core nuclear rocket which can operate at temperatures much higher than the solid core (20-30,000°K). The fundamental problem here is separation of the fissionable material (U^{235} vapor) to prevent its leaving the rocket through its propellant exhaust (H_2). If too much fissionable material is lost, significant contamination of the environment occurs and an immense expense is incurred. Most of the research in this area has been theoretical and concerned with this separation problem, and the problem is still a long way from being solved.

A second alternative which has not been considered to any extent is to use a gas core reactor in a closed system so that separation is of no concern. In this case temperatures on the order of 20-30,000°K are impractical since heat fluxes would be extraordinary. However, one could consider temperatures in the range of 10,000°K as perhaps feasible. This would provide a major step forward relative to presently considered solid core closed loop systems. Also, at such temperatures the MHD generator becomes a compact and efficient conversion device whereas turbomachinery is completely out of the question.

In this paper we will present a review of one possible gaseous fission closed loop system using an MHD generator. Some of the critical problems that would require solution will also be reviewed.

1-7 FEASIBILITY OF A NUCLEAR LASER EXCITED BY FISSION
FRAGMENTS PRODUCED IN A PULSED NUCLEAR REACTOR

G. R. Russell
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Recent experimental work (Ref. 1) indicates that electrical excitation of lasers can be enhanced by irradiating the laser medium with high energy protons. Present calculations show that infrared laser excitation in partially ionized argon can be attained without electrical excitation utilizing a source of fission fragments in a pulsed nuclear reactor. The analysis deals with the excitation of atomic argon irradiated in an optical cavity with fission fragments obtained by passing the reactor neutron flux through thin uranium foils in the cavity walls. Simultaneous numerical solutions are obtained of the electron energy equation, the specie continuity equations, and the rate equations governing the population of atomic excited states. Electron diffusion, three body collisional-radiative recombination, molecular ion formation and dissociative recombination are treated simultaneously in the determination of the electron density. Optically thin free-bound radiative losses are calculated using the theory of Biberman et al. (Ref. 2). Nonequilibrium thin line radiation is included as well as leakage losses from the thin line wings of resonance transitions. A ten level hydrogen-like model is used to calculate the collisional-radiative recombination rate and the populations of the first ten transition arrays of atomic argon. Radiative transition probabilities are calculated using the theory of Bates and Damgaard (Ref. 3). Collisional excitation due to low energy thermalized electrons is evaluated using Gryzinski (Ref. 4) cross sections for optically allowed transitions averaged over a Maxwellian distribution at

the thermalized electron temperature. Excitation due to high energy secondary electrons and primary fission fragments is treated separately using Gryzinski cross sections in the high energy limit corresponding to the Born approximation.

In the solutions of interest for atomic lasers collisional-radiative recombination is the dominant recombination process; dissociative recombination is limited by molecular ion production and does not exceed 20 percent of the three body rate. The degree of ionization is of the order of 10^{-4} and is proportional to the fission fragment flux rate. Electron temperatures are elevated from an atomic temperature of 300°K to values in the range of $1500 - 2000^\circ \text{K}$, and are not strong functions of either the gas density nor the fission fragment flux rate. It is shown that direct excitation caused by high energy fission fragments and secondary electrons leads to population inversions of the 5S-4P array transition which would not occur in a recombining gas at the same electron temperature and density if there were no high energy particles present. Generally, for optical cavities of reasonable lengths for use in a nuclear reactor, threshold population of the upper 5S array cannot be attained utilizing 5S-4P inversions. However, due to subsequent capture of electrons initially produced by fission fragment and high energy secondary electron ionizing collisions, population inversions are also shown to exist at the higher 4d-5P transition array. Threshold values of the upper 4d array of this transition are large enough to provide infrared laser excitation in a cavity having a length of from 50 to 100 cm, where the neutron flux rate is of the order of $10^{14} \text{ cm}^{-2} \text{ sec}^{-1}$, and the gas pressure is about one to two torr.

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2-1 EXPERIMENTS ON THE CONTAINMENT OF SIMULATED FUEL IN UNHEATED AND HEATED VORTEXES*

A. E. Mensing and J. F. Jaminet
United Aircraft Research Laboratories
East Hartford, Connecticut

Experimental investigations were conducted in which the amount of heavy gas contained in light-gas vortexes was measured for both heated and unheated (isothermal) vortex flows. In the vortex flows with heat addition, power was added to the flow by r-f induction heating of the gas within the chamber. The light gas, argon, was injected in a tangential direction either from the end walls or from the peripheral wall. The flow rate, plasma diameter, and power addition were such as to provide a radial gradient of temperature of approximately 50,000 deg K/in. near the outer edge of the plasma. Xenon was employed as the heavy gas and was injected into the vortex at several different locations. Spectroscopic techniques were used to determine both the temperature distribution and the xenon partial pressure within the plasma.

Tests conducted with unheated vortex flows employed a vortex tube much larger than, but geometrically similar to, the vortex tube used in the heated tests. Air was used as the light gas and mixtures of iodine with helium, nitrogen or sulfur hexafluoride were used as heavy gases. Several different heavy- and light-gas injection configurations were used, and the weight flow rates of both the heavy and light gases were varied. The volume-averaged partial pressures of the heavy gas within the vortexes were determined, as were

* This research was supported by the joint AEC-NASA Space Nuclear Propulsion Office under Contracts NASw-847 and SNPC-70.

the radial distributions of the heavy-gas partial pressure.

Comparisons were made of the heavy-gas partial pressures in the heated and unheated flows. For similar geometries and the same light-gas weight flows, the heated vortexes had larger values of the heavy-gas partial pressure in the central regions of the vortex, but less heavy-gas partial pressure at the greater radii. Under the same conditions, the volume averaged heavy-gas partial pressures were about equal in both heated and unheated flows. Radial gradients of static pressure in the heated vortexes were much less than in unheated vortexes having the same flow rates.

2-2 EXPLORATORY PLASMADYNAMIC STUDIES OF VORTEX AND COAXIAL FLOW GEOMETRIES EMPLOYING RADIO-FREQUENCY INDUCTION HEATING*

J. J. Keyes, Jr., and W. K. Sartory
Oak Ridge National Laboratory
Oak Ridge, Tennessee

Experiments are described in which the effect of high energy-density volumetric heating on jet-driven vortex flow of argon and on coaxial flow of helium and argon have been determined. A radio-frequency power source capable of 50 kw output in the range from 0.4 to 4.0 M Hz was used to heat argon and helium-argon plasmas inductively at atmospheric pressure to peak temperatures estimated to be between 10,000 to 15,000°K depending on plasma composition.

Experiments with 2-in.-diameter by 6-in.-long water-cooled copper and quartz vortex tubes have revealed that significant increase in the ratio of tangential velocity to injection velocity above that measured at room temperature is effected when the argon gas is inductively heated to plasma conditions (10,000°K). Exit gas temperatures of up to 7000°K have been measured.

The Oak Ridge National Laboratory facility is unique in that it includes a 6-in.-ID superconducting magnet capable of generating reasonably uniform axial magnetic flux densities of up to 2.3 w/m² over the plasma region. This magnet is intended for use in evaluating the influence of strong magnetic fields on turbulent mixing in plasmas. Initial coaxial flow studies using a 2-in.-diameter quartz outer tube for helium and a 1 1/4-in.-diameter graphite injection tube for argon have resulted in a positive correlation of magnetic flux density and coupling between the radio-frequency field and the plasma. This correlation can best be interpreted as

* Research sponsored by the U. S. Atomic Energy Commission under contract with the Union Carbide Corporation.

suggesting that the magnetic field increases the effective argon concentration in the plasma, presumably due to decreased turbulent mixing.

2-3 EXPERIMENTAL STUDY OF THE EFFECT OF INLET CONDITIONS ON THE FLOW AND CONTAINMENT CHARACTERISTICS OF COAXIAL FLOW

B. V. Johnson
Fluid Dynamics Laboratory
United Aircraft Corporation
East Hartford, Connecticut

Fluid mechanics experiments were performed to investigate the factors which influence the formation and growth of the large eddy structure in developing coaxial shear flows. The tests were performed in a 10 inch diameter chamber with a length of 10 in. The inlet to the chamber was designed for operation with either two or three coaxial streams. Air or Freon-11 was used as the inner-jet gas, and air was used for the buffer stream gas (if used) and the outer stream gas. Flow visualization was obtained by coloring the inner-jet with iodine gas and photographing the flow with high-speed motion pictures. Hot-wire and pitot probes were used to obtain averaged and fluctuating velocity data in the chamber. For certain tests provision was made for smoothing the velocity discontinuities between the streams prior to their entrance into the chamber.

The results from these tests indicate that large eddies, characteristic of the interface between coaxial flows, can be essentially eliminated for flows in short chambers, at conditions simulating those for an open-cycle gaseous-core nuclear rocket engine, by proper smoothing of the velocity discontinuities between the streams at the inlet. The apparent inner-jet gas containment obtained with the best inlet configuration was better than was obtained from previous tests where large velocity discontinuities at the inlet were present.

2-4 SELF-CONFINED ROTATING FLOWS FOR CONTAINMENT

F. K. Moore and S. Leibovich
Cornell University
Ithaca, New York

A number of cylindrically-symmetric flows are described in which a fluid separation may be maintained by rotation, with no nearby walls. These include:

(1) Slender "vortex breakdown" eddies aligned with outer stream rotation.

(2) The Taylor solution for a sphere in a rotating fluid, where we regard the sphere as fluid. In one particular case, the fluid in the sphere is at rest. This possibility is considered in detail because of its possible importance for containment.

(3) Steady nonlinear wave disturbances of a rotating fluid which indicate how enclosures develop in a rotating fluid, and show the effect of radial swirl profile.

(4) A flow related to Hill's vortex, having a stationary core of fluid at rest.

With containment of a heavy fluid in mind, the stability of these flows is discussed. Flows cylindrically stratified by density tend to be unstable, but rotation can reduce amplification rates. Generally, to have the contained fluid at rest is stabilizing, especially if the inner fluid is heavy, and the outer flow is rotational.

Evidence is offered that additional necessary stabilization may be provided by the radiative heat transfer mechanism coupled with heat generation proportional to density. Additional constraints can be provided by an aligned magnetic field.

Finally, the problem of viscous decay of self-contained flows is discussed.

2-5 STABILITY OF TWO-FLUID WHEEL FLOWS WITH AN IMPOSED UNIFORM AXIAL MAGNETIC FIELD

Carl F. Monnin and John J. Reinmann
Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio

The stability of an incompressible two-fluid wheel flow to infinitesimal helical disturbances is studied. The inner fluid is heavy and has infinite electrical conductivity, while the outer fluid is light and is nonconducting. An axial magnetic field is externally imposed on both fluids. This configuration may be viewed as a Rayleigh-Taylor problem in the frame of the rotating fluid and is dynamically unstable. Growth rates increase with increasing axial wavelength and azimuthal mode numbers, but decrease with increasing axial magnetic field. By increasing the magnetic field sufficiently, the system can be made stable to short axial wavelength disturbances for any azimuthal mode.

2-6 STABILITY CONSIDERATIONS FOR A TRANSPARENT WALL
IN A GASEOUS NUCLEAR ROCKET

C. K. W. Tam, D. B. Goracke and W. S. Lewellen
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The stability of infinitesimal disturbances on an inviscid, incompressible model of coaxial flow around a cylinder of stationary fluid of differing density separated by a thin, flexible wall is studied. The pinch mode of disturbance is found to be the most unstable. The wall strength, required to insure that no disturbance will grow along the boundary, is determined as a function of density ratio and the dynamic pressure of the flow. A numerical example indicates that adequate strength can be obtained within the thickness limit imposed by the heat absorption constraint existing in the nuclear light bulb concept of a gaseous nuclear rocket, but the margin is close enough to suggest that other possible additive effects merit further analysis.

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Future engineering devices for propulsion and power generation may employ gases at extremely high temperatures, of the order of $50,000^{\circ}$ Kelvin. In such a device thermal radiation is likely to be the dominant energy transfer mechanism, the energy being radiated between different opaque regions of the gas rather than between walls containing a transparent gas. Now in order to transfer such large net heat fluxes, or the order of megawatts per square centimeter, very large temperature gradients will be involved, perhaps of the order of ten-thousand degrees per centimeter. Such an extreme state of nonequilibrium may not be attainable, due to the fact that the state of the gas may be unstable with respect to small disturbances. That is, there may be conditions under which an infinitesimally small perturbation such as a sound wave may cause the state of the system to change spontaneously to some different stable state.

The cause of such an instability may be easily illustrated. Consider a wave in a radiating gas in which the opacity, or volumetric absorption coefficient, of the gas is an increasing function of temperature. If a large net flux of radiation is present a local increase in temperature will

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lead to an increase in opacity, which will cause more absorption of the radiative flux. The resultant increase in the heating of the gas will cause the temperature to increase further, leading to a runaway situation. This phenomenon has been observed in experiments involving the heating of a shock wave by a laser beam, but there is as yet no experimental evidence of an instability of a quiescent gas heated by radiation. This cannot happen in a uniform gas having no net heat flux, because then a region of temperature and opacity increase will be a net emitting instead of absorbing region; the energy excess will be radiated away and equilibrium will be regained.

There seem to be three factors which are necessary to this proposed mechanism for the amplification of waves. First, there must be a source of radiation present of higher temperature than the medium supporting the wave; second, the wave must be sufficiently opaque for the absorption of radiation to be a significant source of energy; and third, the opacity of the gas must be an increasing function of temperature so that a runaway effect is possible. These considerations lead to the following very important questions which are answered by this research.

(a) Are there any conditions under which an infinitesimally small disturbance, i. e., an ordinary fluctuation of the gas, can grow into one of these radiation driven shock waves?

(b) How is the criterion for wave growth dependent upon such properties as the flux of radiation or the rate of increase of opacity with temperature?

(c) If such waves can grow in a radiating gas under what conditions will they cause a given radiation heat transfer problem to not have a stable steady-state solution?

A steady-state heat transfer problem is set up in which energy is transferred from a hot wall to a cooler wall by thermal radiation. The gas is assumed to be a perfect gas in local thermodynamic equilibrium. Molecular heat conduc-

tion and viscosity are ignored and a one-dimensional geometry is assumed. The radiation pressure and energy density are neglected. An opacity is assumed which is an average over photon frequencies, but which depends on temperature and pressure. The stationary gas of arbitrary optical depth is contained between two black walls of constant temperature. We then ask what are the fluctuations, or natural oscillations of this steady nonuniform radiating gas.

The equations of motion for the fluctuations of a radiating gas are derived through the usual linearized perturbation analysis of the equations of unsteady compressible gas dynamics. The result is a partial differential equation (having spacially varying coefficients) which is fourth order in space and third order in time which governs the behavior of the oscillations.

The determination of the normal modes of oscillation of this gas requires the solution to an eigenvalue problem, the eigenvalues being the allowed complex frequencies selected by the boundary conditions. The wave equation with varying coefficients is solved by the WKB method. A computer program finds the roots of the determinant which results after application of boundary conditions. The complex roots, the parts of which are the frequency of oscillation and the damping or growth rates, are found in the form of a root locus as a function of increasing net heat flux. An example is given in Figure 1.

It is found that there exists a critical heat flux below which the gas is stable. For larger net heat fluxes than this critical value a mode of oscillation will grow exponentially with time, indicating that the given radiative heat transfer problem does not have a stable solution.

Conclusions

The broad features of the proposed mechanism of an instability driven by absorption of radiation in a gas have been confirmed by the results of an eigenvalue problem, which may be summarized as follows.

(1) A previously unsuspected instability may arise in a nonuniform radiating gas, at least for the particular boundary conditions of black walls of constant temperature.

(2) The instability can occur only for moderately high temperatures. For low temperatures the radiative transfer is not strong enough to drive the instability, and for extremely high temperatures the radiative transfer is so efficient as to cause disturbances to be isothermal, which also is stabilizing.

(3) The instability can occur for opacities which vary more strongly than the fourth power of the temperature. That is, if $\alpha \sim T^m$ the instability seems possible only for m larger than four. A typical neutral stability curve is given in Figure 2.

(4) The instability may arise only for a gas which is optically thick. However no unambiguous trend toward greater or lesser stability could be established based on comparisons between average photon wavelength, disturbance wavelength, and distance between the walls.

(5) The lowest frequency normal modes will be most unstable or will become unstable first as the net radiative flux is increased.

(6) The criterion for the growth of traveling acoustic waves is not a reliable indicator of the onset of instability as predicted by the eigenvalue problem. This means that the boundary conditions do substantially influence the stability of the system, even for waves of short wavelength, and systems with different boundary conditions must therefore be treated on an individual basis.

In summary, previous work on fluctuations in a radiating gas has been extended to include an opacity which is a function of temperature and pressure and most importantly, to include a net radiative heat flux and gradients in the thermodynamic variables. These extensions allow the investigation of an instability driven by the absorption of radiation by waves in the gas. The effect of this will be to limit the

maximum possible net radiative heat flux in a problem to a value which can be substantially lower than that predicted by the usual steady-state heat transfer analysis.

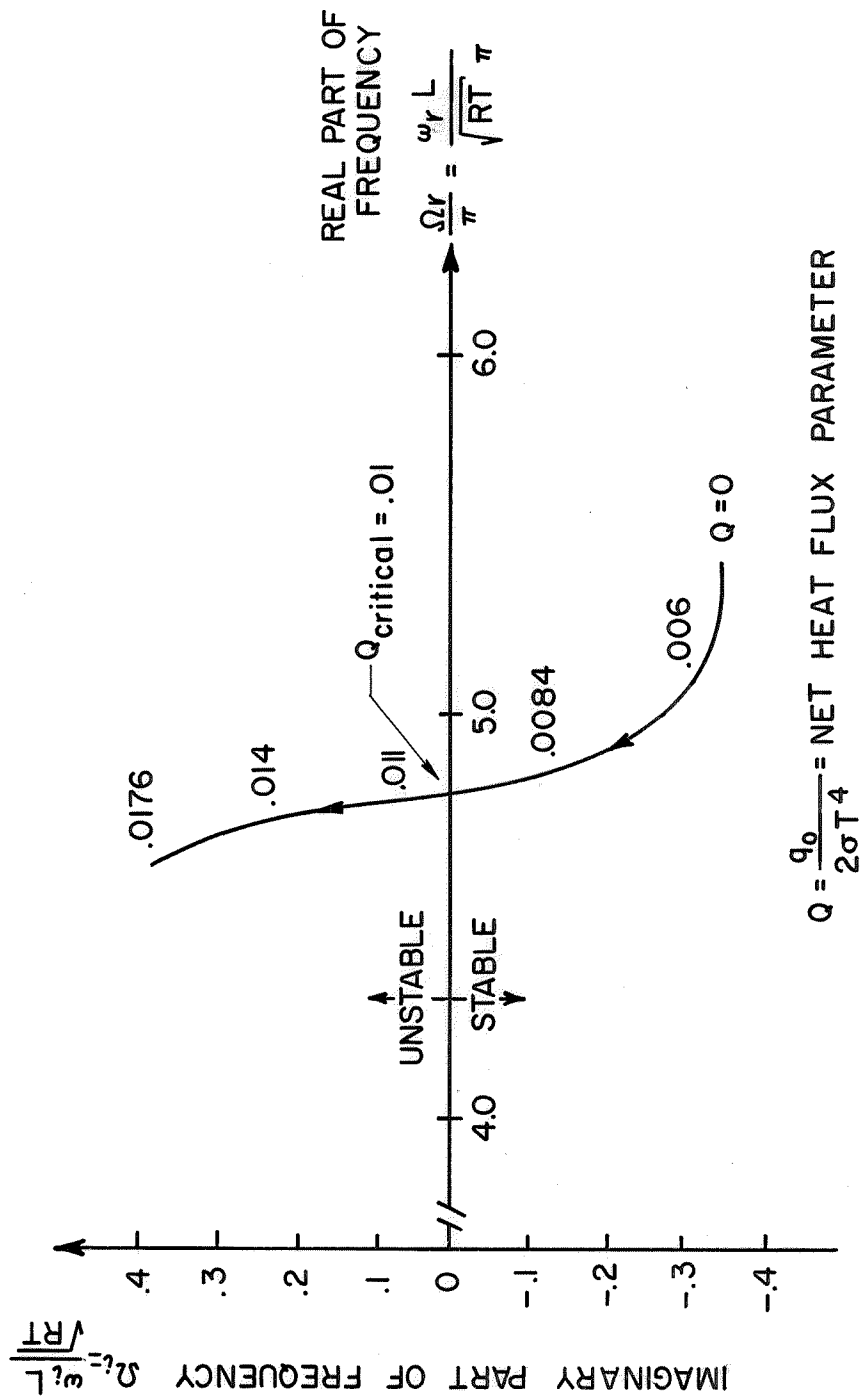


FIG. 1 TYPICAL ROOT LOCUS

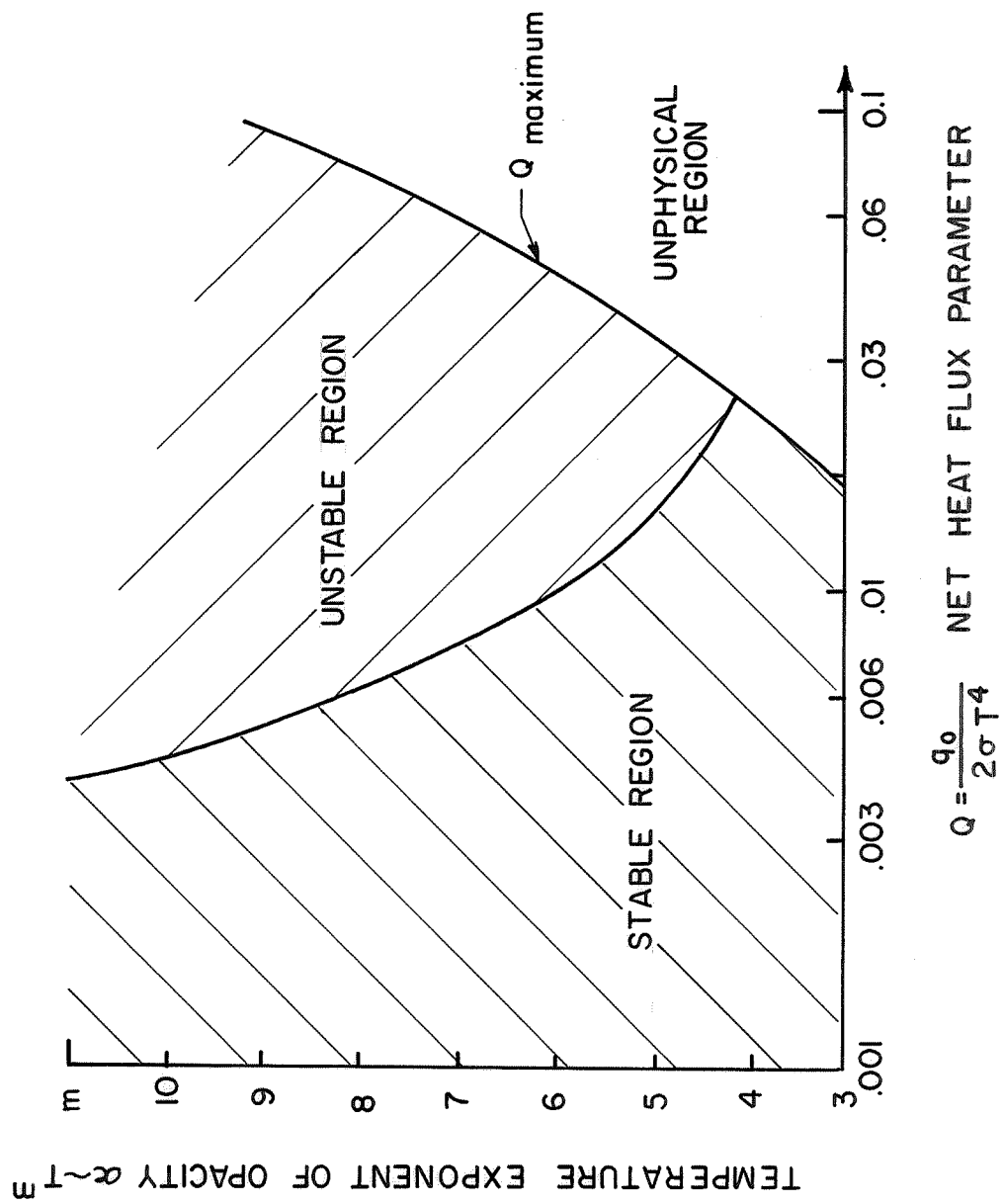


FIG. 2 NEUTRAL STABILITY LOCUS

2-8 GAS-CORE NUCLEAR ROCKET CONCEPT WITH FUEL SEPARATION BY MHD-DRIVEN ROTATION

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A mixture of two gases with differing molecular weight can be separated by the centrifugal force developed in a solid body-like rotation (Ref. 1). There are conceivably at least three different methods of applying the centrifuge principle to a gas-core nuclear rocket in which the light propellant gas must be separated from the heavy fuel gas (Fig. 1). The first proposed scheme (see, e.g., Ref. 2) is to induce the gas rotation by the tangential injection of the propellant gas into the nuclear reactor cavity (Fig. 1(a)). According to Ref. 2, this configuration has been proved to develop into a vortex flow which does not operate favorably as a centrifuge. The second conceivable idea is to rotate the cavity chamber mechanically (Fig. 1(b)). Because the centripetal acceleration in such a device would exceed 1,000,000 g's, it would be necessary to apply a gas pressure of at least 10,000 atmospheres on the outside wall of the cavity chamber to reduce the hoop stresses in the rotating wall to a workable level. The friction loss at the outside surface of the rotating wall then becomes prohibitively large, i.e., an order of magnitude greater than the MHD-driven rotation described below, which therefore renders the scheme impractical. In the third possible scheme, the $J \times B$ force acts on the gas in the region near the cylindrical wall of the cavity to drive the flow in a rotating motion (Fig. 1(c), Ref. 3). This third scheme is free of the above impediments, and therefore warrants further study. The present

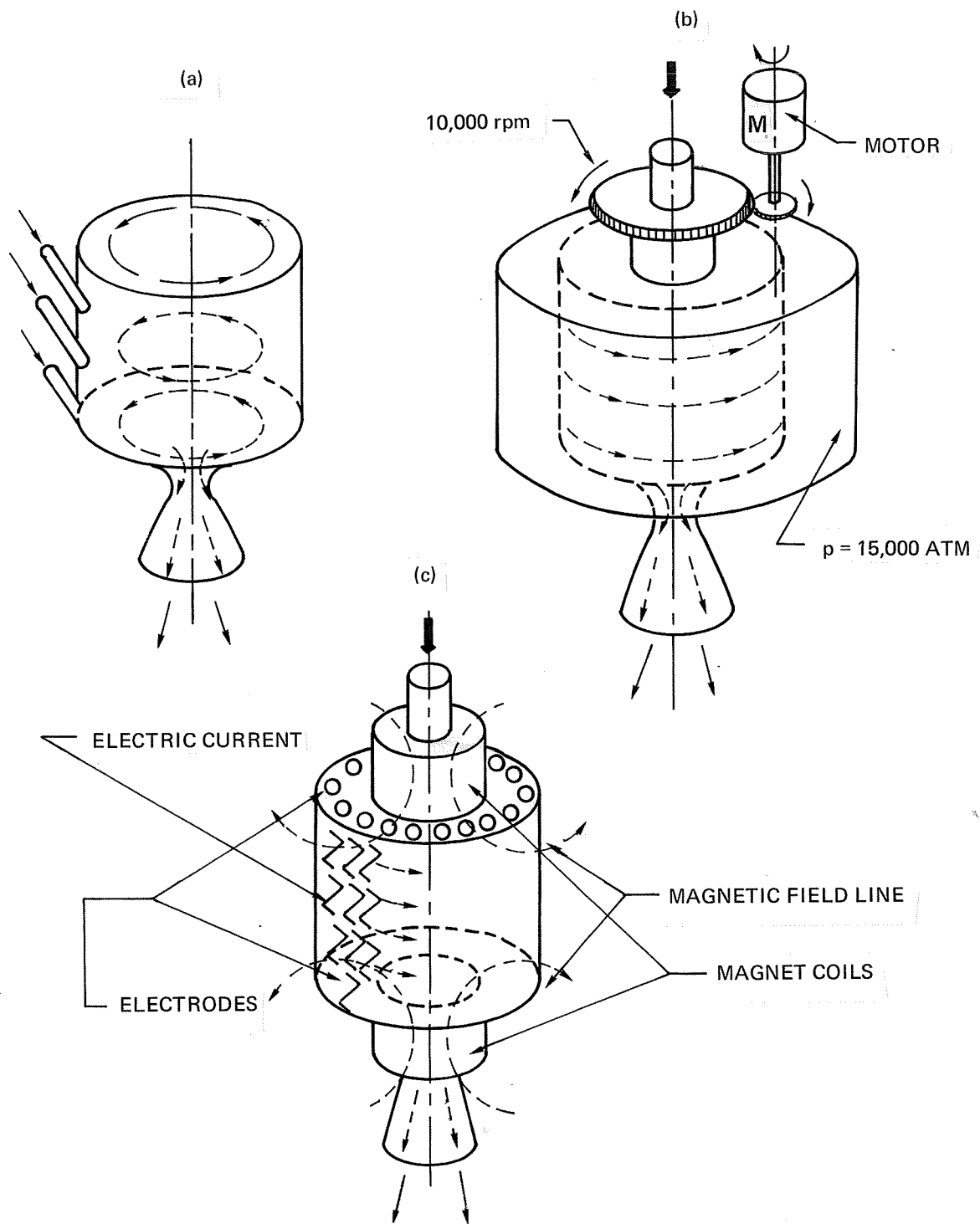


FIG. 1 CENTRIFUGAL SPECIES SEPARATION SCHEMES FOR GAS-CORE NUCLEAR ROCKET. (a) FLUID INJECTION TYPE, (b) MECHANICAL ROTATION TYPE, (c) MHD-CENTRIFUGE

paper describes the results of a preliminary experiment aimed at testing the effectiveness of the MHD-centrifuge scheme in creating a concentration variation and discusses the projected performances and the problems associated with it.

A preliminary study on the feasibility of the MHD-centrifuge scheme for separating two gases has been carried out at Ames Research Center (Ref. 3). The apparatus was designed with the objective of attaining a rotational motion of the gas which approaches as nearly as possible that of solid-body rotation when there is no flow in the axial direction along the centerline. By applying the Lorentz force resulting from the interaction of a radial magnetic field of about 0.2 tesla and an axial electrical current of approximately 2000 amperes, a significant rotational speed was achieved in the mixture of xenon and helium. The rotation of the gas, evidenced by a three-fold difference in pressure between the centerline region and the wall surface, was accompanied by a measurable degree of separation between the xenon and helium. The ratio of enrichment of the heavy species near the wall was determined spectroscopically to be around 2. Within the uncertainty expected of this preliminary test, the experimental result seemed to follow the theoretical prediction. A further experiment is planned to determine the effect of the axial flow motion on the degree of concentration enrichment.

Assuming that the basic MHD-centrifuge hypothesis is valid and also that the axial flow does not affect the performance, feasibility of a prototype nuclear rocket is studied here. The schematic and the operating characteristics of the rocket operating on the MHD-centrifuge principle is shown in Fig. 2 and in Table 1. The cavity is typically 6 meters in diameter and 6 meters long. The radially oriented magnetic field is produced by a pair of cryogenically-cooled magnet coils and has a strength of around 0.5 tesla near the cavity wall. The magnets draw negligible amount of power, which can be powered from the same source that supplies the electrode currents or from a separate power supply.

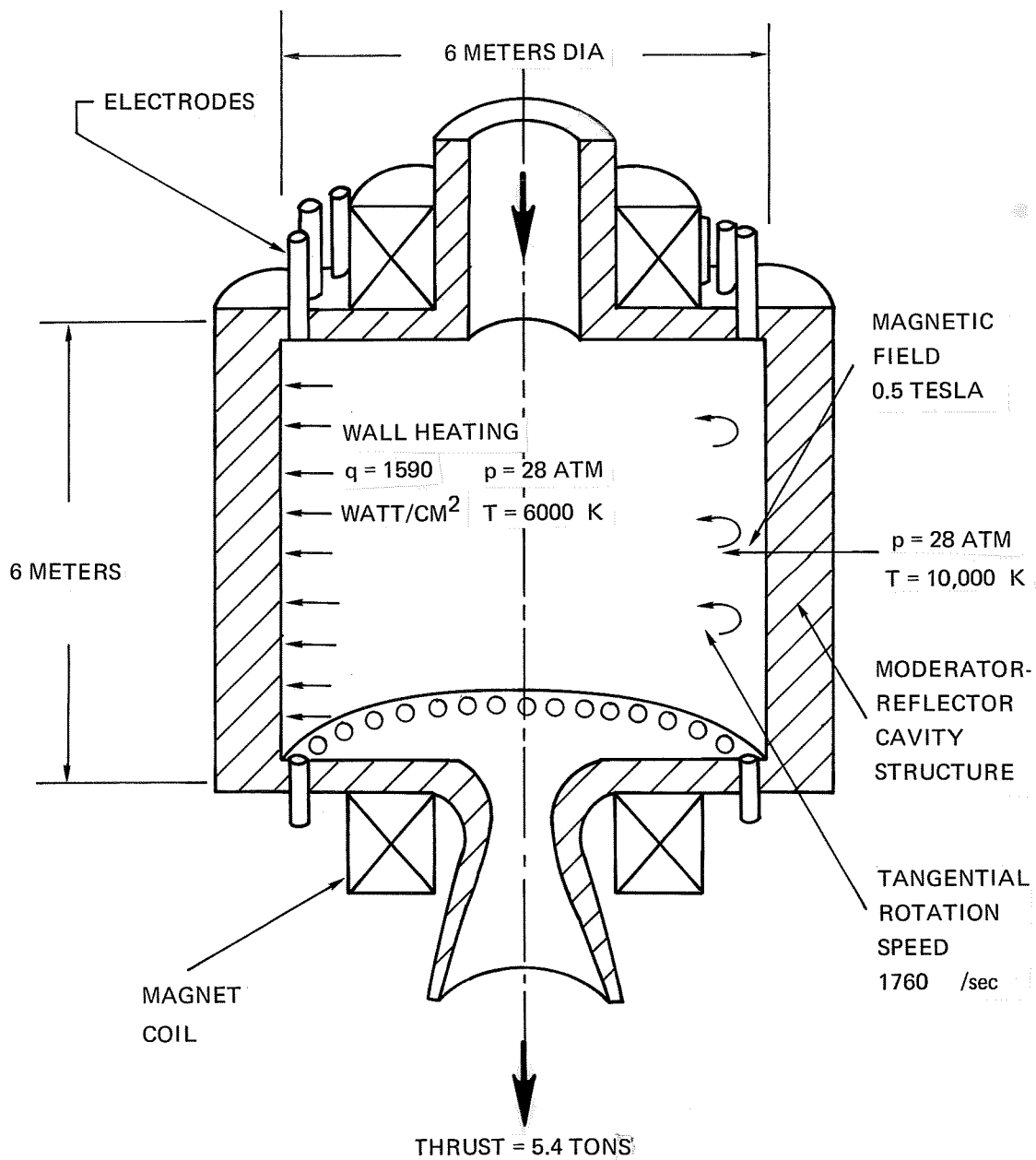


FIG. 2 SCHEMATIC OF GAS-CORE NUCLEAR ROCKET CAVITY CHAMBER WITH SPECIES SEPARATION BY MHD-DRIVEN ROTATION

Total electrical current of around 15,000 amperes flows through 180 pairs of segmented electrodes. The pressure is around 18 atmospheres at the centerline and 28 atmospheres at the wall, the maximum tangential rotation velocity being around 1.8 km/sec. The propellant gas is introduced along the centerline of the cavity and flows through the center of the cavity at a low velocity. The propellant gas absorbs heat from the fuel gas primarily through radiation and, to a lesser extent, by convection. The radiative transfer of energy to the hydrogen is enhanced by the radiative coupling between the uranium in the fuel region and the small amount of uranium (about 0.0002 mole fraction) which has diffused into the hydrogen at the centerline region of the cavity. The temperature varies from around 10,000°K at its peak near the cylindrical wall to around 6000°K at the centerline, which corresponds to a specific impulse of around 1500 sec. The thrust of the rocket is typically 5 tons.

The overall system is shown schematically in Fig. 3. The liquid hydrogen flows first through the superconducting magnet coils, maintaining them at cryogenic temperatures. The liquid hydrogen is then pressurized by a booster pump to a pressure of around 1640 atmospheres before it enters the heat-exchanger comprising the moderator-reflector wall of the cavity. The hot gas emerging from the heat-exchanger drives the first-stage turbo-electric generator that supplies half the required MHD-power. The pressure is around 107 atmospheres at the exhaust of the first-stage turbine. The exhaust is fed again into the heat-exchanger to drive the second-stage turbine. It is estimated that by employing a 2-stage turbo-electric generator system, all required MHD-power can be obtained. The power reclaimed by the turbo-generators represents only 3% of the energy transmitted to the wall; however, the remaining 97% of heat entering the cavity structure is removed through a liquid-metal cooling system which exhausts its energy through a radiator which is at least 1200°K surface temperature. A fraction of the radiated power can be recovered by an auxiliary power generator

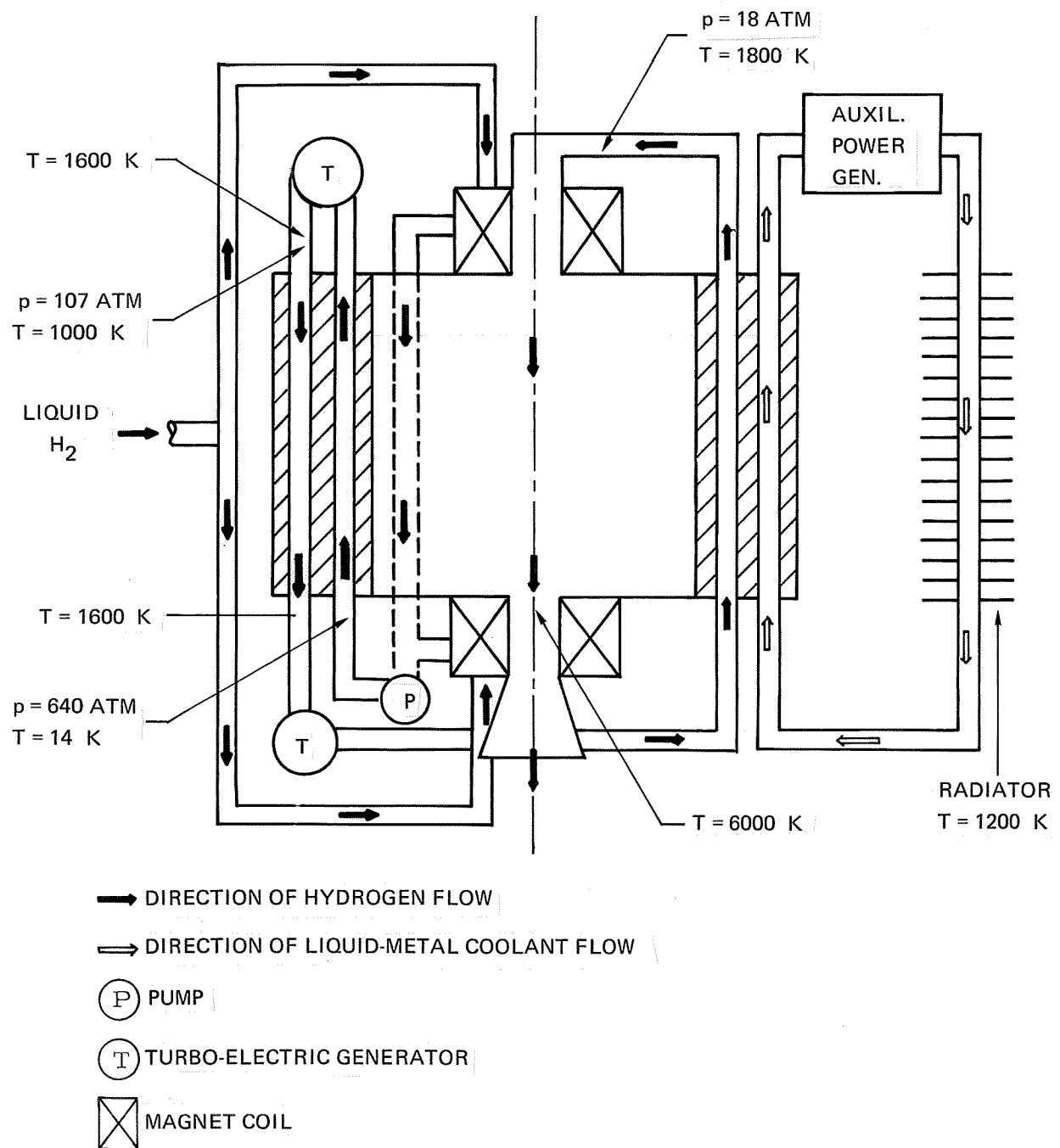


FIG. 3 SCHEMATIC OF POWER SUPPLY SYSTEM OF A PROTOTYPE GAS-CORE NUCLEAR ROCKET WITH FUEL SEPARATION BY MHD-DRIVEN ROTATION

system which supplies power in the starting process and also drives other utilities.

Table 1 shows the estimated power and weight breakdown of a typical MHD-centrifuge gas-core nuclear rocket. The performance figures in the table are derived from the following assumptions:

(1) The heat-transfer efficiency of the rocket chamber is 17%, i.e., 17% of the fission energy is transferred directly into the propellant gas in the cavity chamber. An additional 3% of the energy is added in the regenerative pre-heating, making the total heating efficiency 20%.

(2) The wall friction coefficient is 1.5 times that in a fully developed turbulent pipe flow.

(3) The wall heat transfer coefficient including the radiative transfer is twice that of a fully developed turbulent pipe flow.

(4) The radiator system weighs 15 kg per square meter of radiator area (see, e.g., Ref. 4).

(5) The cavity wall structure comprising the moderator-reflector is 1 meter thick, its average specific gravity being 5 (beryllium oxide moderator with heavy metal reinforcement, see Ref. 5).

(6) The turbo-electric generator system weighs 2 kg per kilowatt of output.

As indicated in the table, the resulting overall thrust to weight ratio is around 1:160. The first 3 assumptions listed above are critical in the performance estimate, and therefore research should be directed to resolve these three questions. An experimental device oriented toward answering these unknowns is currently being designed at Ames Research Center.

Table 1. Estimated Operating Characteristics and Weights

Dimension and Performance

Cavity wall diameter	6 m
Cavity length	6 m
Weight of uranium contained	10.2 Kg
Specific impulse	1470 sec
Thrust	5.4 ton
Thrust-to-weight ratio	1/161

Thermodynamic Characteristics

Pressure at center	17.8 atm
Pressure at cavity wall	27.6 atm
Temperature of hydrogen at center	6000°K
Peak temperature of uranium	10,000°K
Concentration of uranium at center	0.0002
Concentration of uranium at wall	0.028
Hydrogen-to-uranium mass flow ratio	21.3
Total mass flow rate	5.1 Kg/sec
Peak tangential rotation velocity	1760 m/sec
Mach number of uranium at peak velocity	2.3

MHD Characteristics

Magnetic field strength at wall	0.5 tesla
Number of electrode pairs	180
Electrode current to individual electrodes	84 amp
Total electrical current	15200 amp
Voltage gradient	8.9 volt/cm
Anode-to-cathode overall voltage	5350 volt

Heat Transfer Characteristics

Cavity surface temperature	2500°K
Peak temperature in regenerative system	1800°K
Peak temp. in liquid-metal cooling system	1400°K
Radiator surface temperature	1200°K
Wall heat-transfer rate	1590 watt/cm ²
Radiator area	26300 m ²

Power

Power dissipated in wall friction	80.4 Mw
MHD arc power	81.4 Mw
Booster pump	4.5 Mw
Magnet	<0.01 Mw
Power generated by turbo-electric system	85.9 Mw
Power transmitted to propellant	561 Mw
Power transmitted to wall	2246 Mw
Power radiated	2160 Mw
Total power generated by fission	2807 Mw

Weight

Cavity structure, moderator-reflector system	368 tons
Cryogenic magnet system	36 tons
Turbo-electric generator system	80 tons
Radiator system	394 tons
Total weight of engine	878 tons

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3-1 CURRENT STATUS OF THE ANALYSIS OF THE OPTICAL SPECTRA OF URANIUM*

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Uranium has one of the most complex optical spectra of any element. It is estimated that over 300,000 lines of U I and U II can be observed and measured with modern, high-resolution apparatus. New high-resolution spectroscopic systems and rapid precision data-reduction techniques are being used at this laboratory to produce a new description of the uranium spectra. The present line list contains information on about 25,000 lines, of which 13,000 have a wave number accuracy better than 0.01 cm^{-1} . About 10,000 lines have been classified to 1130 levels of U I and U II, but only a few of the levels have been assigned to an electron configuration. Although the numbers of classified lines and levels appear large, much experimental work remains to be done before adequate descriptions of the uranium spectra exist. Some theoretical calculations have been made of the energy level structure of the low-lying configurations of U I through U VI. Agreement with known experimental levels of U I and U II is reasonably good for the lower levels. These calculations lead to ionization potentials for U I through U V, which are respectively: 6.25 ± 0.5 , 10.8 ± 1 , 18.9 ± 1 , 32 ± 2 , and 47 ± 2 volts. Both theoretical and experimental work are continuing, and will provide a greatly expanded analysis of the optical spectra of uranium.

*Work performed under the auspices of the U.S. Atomic Energy Commission.

3-2 STATUS OF OPACITY CALCULATIONS FOR APPLICATION TO URANIUM-FUELED GAS-CORE REACTORS

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In the gas-core reactor concept, the working fluid, which is always a gas, is heated by thermal radiation from a hot, fissioning uranium plasma located in the center of a chamber. If the reactor is part of a rocket engine, the optimum working fluid is hydrogen because its low molecular weight contributes to a high specific impulse when the hydrogen is expanded through an exhaust nozzle. Unfortunately, hydrogen is not sufficiently opaque at temperatures below 6000°K to prevent excessive thermal radiation from reaching the chamber walls and causing excessive wall heating. Hence the hydrogen is seeded with some material to increase its opacity. To assess the feasibility of the gas-core reactor concept, the opacities of hydrogen, seeds and uranium plasma must be calculated. This paper is a review of such work.

A large number of opacity calculations have been done for hydrogen. Recently I have performed calculations for pressure from 100 to 1000 atm. and temperatures from 1667 to $50,000^{\circ}\text{K}$, taking into account 15 absorption processes and using the latest and most reliable composition calculations. The results are probably accurate to within a factor of four for reasons that are outlined.

The most promising seeds are small particles of silicon, carbon, or tungsten. Opacities of the small particles have been calculated by Krascella, (Ref. 1). At high enough temperature, the small particles either vaporize or react chemically with hydrogen, drastically changing their opacity. The

opacity of tungsten vapor has been calculated at United Aircraft (Ref. 2). The opacity of the reaction products of carbon and hydrogen has been calculated by Main (Ref. 3). These are both order of magnitude calculations.

The opacity of uranium was calculated by Parks, Lane, Stewart, and Peyton, (Ref. 4), based on x-ray energy levels and ab initio energy level calculations performed by Waber, Cromer, and Liberman (Ref. 5). Comparison with arc spectra indicates the need for adjustment of two energy levels in Park's theory, but the original opacities should be accurate to within a factor of 10.

The opacity calculations described above are probably accurate enough to assess the feasibility of a uranium-fueled gas-core reactor, but the confidence level is not yet satisfactory.

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3-3 CONDITIONS FOR LOCAL THERMODYNAMIC EQUILIBRIUM IN URANIUM

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Possible effects on uranium opacities due to non Local Thermodynamic Equilibrium (LTE) populations of bound states are investigated. The simple model used to calculate the pertinent atomic parameters is described. Although the model is capable of giving only qualitative results, it gives estimates of situations where a uranium plasma will show deviations from thermodynamic equilibrium. Temperatures and densities at which these deviations become significant are given. Some cases where non LTE effects are important are discussed in detail and the LTE values of the opacity and source function are compared to the correct values.

3-4 BOILING POINT OF URANIUM

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Current techniques for boiling point determinations rely on extrapolations of low temperature vapor pressure data (usually collected below 2500°K) through the Clausius-Clapeyron equation. Since the temperature limitation is, in most cases, difficult to overcome, it is necessary to rely heavily on indirect methods for the evaluation of boiling points. Under special environment conditions there is evidence that an interpretation of uranium plasma electrical characteristics can lead to reasonable estimates of the boiling point.

The device used to generate the uranium plasma, the University of Florida high pressure uranium arc, is described. Details of the electrical power, cooling, high pressure, gas, and data acquisition systems are given.

A modification of the Nottingham equation for electric arc potential versus current is presented. The application of this arc electrical characteristics model is discussed in terms of the determination of the boiling point of the uranium anode. The evaluated boiling points of uranium between 1 atmosphere and 7 atmospheres are compared with the extrapolations of other authors.

3-5 SPECTROSCOPIC STUDY OF A URANIUM ARC PLASMA

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This paper reports on measurements of temperatures, particle densities, emission and absorption coefficients of a uranium arc. The motivation for this research is to acquire fundamental knowledge of the physical properties of uranium plasmas which will in turn eventually lead to the design of a self-sustaining fissioning plasma.

The arc is generated in a high pressure cell capable of withstanding pressures up to 100 atmospheres. The current passes between a tungsten pin cathode and a uranium pellet anode. A cover gas of helium is used and substantial vaporization of uranium takes place as the pellet temperature rises and the arc stabilizes. The atomic characteristics of the helium and uranium are such that the emitted line radiation originates primarily from singly-ionized uranium.

Spectroscopic diagnostics were used throughout the investigation. Several methods of temperature determination were employed including Boltzmann plots, relative line intensities and brightness emissivity methods. Although there are difficulties associated with each method all temperature measurements were found to lie in the range of 7500-12,000°K.

The measurements of emission and absorption coefficients of the plasma were taken over the pressure range of 3-15 atmospheres and current range of approximately 15-50 amperes. The corresponding partial pressure of uranium over this range was estimated to be 0.1 - 0.5 atmospheres.

3-6 URANIUM PLASMA OPACITY MEASUREMENTS*

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Absolute opacities of uranium plasmas (2800-8800 Å) are measured using a gas driven shock tube (Ref. 1). Temperatures (7500-12,000°K) and partial pressures (1/50 - 1/5 atmos.) approach those anticipated at the hydrogen-uranium interface of proposed gaseous core nuclear reactors. At these conditions uranium (UI, UII, UIII) is essentially the only spectroscopically active constituent of shock tube test gases composed of 0.2 - 2.0% UF₆ in neon (Ref. 2). Absolute opacities at 5000 Å are measured photoelectrically both in emission and in absorption. Time resolved photographic recording was used to determine the variation of opacity with wavelength. Visible opacities are 2-5 times smaller than theoretical predictions (Ref. 3), depending on plasma state. The relative contribution to the opacity from the continuum appears to be tenfold greater than predicted. The variation of opacity with wavelength was found to fit theory well between 4000-8800 Å, but observed opacities decreased rapidly in the UV whereas theory predicts they should increase strongly.

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3-7 GENERATION OF A FISSIONING PLASMA

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The radiation and transport properties of a uranium plasma are currently being measured and calculated by several research teams. Usually, local thermal equilibrium is assumed. However, when fissions occur, the high energy (65 to 100 Mev) fission products will cause extensive ionization and excitation of a nonequilibrium nature. The resultant plasma radiation properties are unknown and practically impossible to calculate. This paper describes the preliminary calculations and an experimental device to be used to investigate the effects of fission products on a uranium plasma. Experiments will be conducted for both "pure" uranium plasmas and uranium plasmas containing cover gases, such as argon or helium.

4-1 NEUTRON KINETICS OF CAVITY REACTORS

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A theory is presented that describes power level variation in a cavity reactor produced by density changes in the gaseous nuclear fuel within the cavity. The effects of a density change are accounted for in terms of a cavity grey-ness, which is the ratio of the net thermal neutron current to the thermal neutron flux at the cavity wall. The nuclei of the fissionable gas in the cavity are assumed to undergo fission only by thermal neutrons, to neither moderate nor absorb fast neutrons, and to be purely absorbing for thermal neutrons. Fast neutrons released by fission and by delayed-neutron precursors leave the cavity, are moderated to thermal energy in the reflector, and diffuse monoenergetically thereafter until they leak from the reflector or are absorbed either in the cavity or in the reflector.

On this basis, we show that for slowly-varying, small perturbations of the gas density in the cavity the percent change in reactor power level per unit time is given by

$$\frac{1}{P(\tau)} \frac{dP(\tau)}{d\tau} = \frac{\rho(\tau)}{\ell\rho(\tau) + \beta/\lambda} + B(\tau) \frac{d\Gamma(\tau)}{d\tau} \quad (1)$$

where $\rho(\tau)$ is the reactivity, $\ell\rho(\tau)$, the prompt-neutron lifetime, β , the fraction of delayed neutrons, $1/\lambda$, the average delay time, $\Gamma(\tau)$, the cavity greyness, and $B(\tau)$ is a coefficient that measures the sensitivity of the reactor to a change of the boundary condition at the cavity wall. This expression differs from the ordinary reactor kinetic equation for

solid core reactors because of the additional term accounting for changes in the boundary condition at the cavity wall.

Reactivity, the coefficient $B(\tau)$, and prompt-neutron lifetime are evaluated for both spherical and cylindrical cavities. For cavity radii near the minimum critical radius, below which a self-sustaining reaction cannot be maintained, all changes in gas density are small perturbations, since the available reactivity is small, and delayed-neutron precursors determine the reactor time constant. As cavity radius increases, however, the prompt-neutron population determines the reactor time constant, and Eq. (1) applies with $\beta = 0$.

Finally, some implications for reactor stability are presented. We find that an accumulation of gaseous fuel near the cavity wall can lead to instabilities for certain cavity radii.

4-2 COUPLED FLUID AND NEUTRONIC OSCILLATIONS IN HIGH-TEMPERATURE GASEOUS URANIUM

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Desire for high nuclear rocket propulsion capability has led to interest in gaseous-core nuclear rockets. Concepts advanced to date generally have required large volumes of gaseous uranium (or possibly plutonium). The existence of a large volume of a gas leads to concern about the possibility of fluid oscillations in the gas. In addition, the gaseous uranium would have an intrinsic density-dependent heat source (from nuclear fission). It is well known, however, that unstable fluid oscillations of acoustic character can exist in a compressible fluid with a density-dependent heat source. This type of instability is a recognized problem in the design of chemical rockets and jet-engine after-burners. In this paper, we shall discuss acoustic oscillations in a uranium gas with a fission heat source. We also shall discuss the feedback to the oscillations caused by external (reflector) moderation and diffusion of neutrons.

We consider a simple model of a uniform infinitely long stationary gas bounded in the transverse direction by a neutron reflector and heat sink. We look for the critical wavelength (above which there is instability) for an acoustic wave propagating in the longitudinal direction. We assume that the critical core length is one-half the critical wavelength (or the distance between nodes of the wave). More complex relations between core length and wavelength would occur if we were to consider real end conditions (e.g. nozzle, injector).

First, we study the case with no neutronic feedback (Ref. 1 and 2). It can be shown, after making some reasonable assumptions, (Ref. 2) that this simple stability criterion applies

$$\lambda^2 \leq \frac{4\pi^2 K_O T_O (\gamma - 1)}{P_O (2 - \gamma)} \quad (1)$$

where λ , K_O , T_O , P_O , γ are wavelength, coefficient of radiant heat transfer, temperature, fission power density and ratio of specific heats. Critical wavelengths for reference cases were in the neighborhood of three feet, whereas reference core lengths of about ten feet generally are cited.

Next, we explore the influence of neutronic feedback (Ref. 3). We assume the core to be transparent to fast neutrons and to be a pure absorber for thermal neutrons. Age theory is used to represent the slowing down process in the reflector. Diffusion theory in the reflector and blackness theory boundary conditions at the core-reflector interface are used to treat thermal neutrons.

Neutronic feedback is found to have a stabilizing influence. The degree of stabilization, however, is a strong function of the reflector material. The smaller the migration area, the greater is the tendency of neutronic feedback to take effect at the location of the disturbance which caused the feedback, and the greater the stabilizing influence of neutronic feedback. Thus, light water is very effective and stabilizes the system. Graphite and beryllium reflectors, however, merely increase the critical wavelength from three feet to five and seven feet respectively.

At high temperatures and pressures relevant to a gaseous core rocket, the uranium will be ionized and behave as a plasma. Some preliminary analysis of plasma effects has been made (Ref. 4) with a two-fluid model, but a more detailed study will have to be made before definitive conclusions can be established.

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43 THE RADIANT HEAT FLUX LIMIT OF BY-PASS FLOW IN A URANIUM PLASMA ROCKET

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The uranium plasma nuclear rocket is a proposed propulsion system which features a high specific impulse (1500 to 2500 sec.) and relatively high thrust (10^5 to 10^6 lb.) One type of configuration is known as the "coaxial flow" concept. This flow system employs a cylindrical geometry with a low-velocity fissioning uranium plasma flowing axially down the centerline of the reactor cavity. High-velocity hydrogen propellant is injected coaxially around the fuel. Heat generated in the uranium plasma is transferred by thermal radiation to the propellant, thus increasing the enthalpy of the propellant. The propellant is then expanded through the nozzle, giving the desired thrust and specific impulse.

The system is externally moderated; therefore, neutrons which are thermalized in the moderator must travel through the hydrogen propellant before they can cause fissions in the uranium plasma. A recent study (Ref. 1) shows that the hot hydrogen propellant acts as a poison in the reactor, thus causing the critical mass to be very large.

A study done several years ago (Ref. 2) suggested the concept of "bypassed flow" to reduce fluid mixing. In the concept of Reference 2 the velocity of hydrogen surrounding the uranium plasma was reduced rather than the amount of hydrogen between the moderator and the uranium plasma.

The object of this study is to reduce the amount of hydrogen between the moderator and the uranium plasma and then to determine the trade off between the decreased critical mass

and the increased wall heat flux. This was done by using the bypassed flow concept. In this idea a small fraction of the total hydrogen flow is passed through the cavity. The rest of the hydrogen flow is added just upstream of the nozzle. This kind of bypass has two advantages. First, the flow area is reduced which decreases the volume (and therefore the mass of hydrogen) between the moderator and uranium plasma. Second, since a constant amount of energy is generated in the uranium plasma and a small fraction of the propellant is used to convect this energy out of the cavity, the average temperature of the propellant in the cavity is increased. The resulting density decrease further decreases the mass of hydrogen between the moderator and uranium plasma.

Using a radiative-convective analysis, this study shows that 80 percent of the flow could be bypassed. This results in the amount of hydrogen between the moderator and the uranium plasma ranging between 4 to 20 percent of that in the nonbypass case. The exact percentage was not calculated in the present analysis. It would actually be determined by whatever changes in fluid mixing would result from the new flow pattern. The maximum wall heat flux increased from near zero to about $1/2 \text{ kw/in}^2$. This study did not examine the new problem of mixing the bypassed flow with the through flow.

The overall conclusion of this study is that a large fraction of the hydrogen propellant can bypass the engine cavity without causing an excessive radiant heat flux on the cavity wall.

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4-4 A STUDY OF THERMAL RADIATION ABSORPTION PROCESSES IN GAS CORE REACTORS*

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In the gaseous core reactor concept, thermal radiation is absorbed by a gaseous working fluid. Since the gas is essentially transparent to the spectral emission of the uranium gas core, an intermediate heat transfer mechanism must be employed to heat the gas. This can be accomplished by seeding the gas with submicron-sized particles which have a high radiant energy absorption coefficient. The seeded gas is grey to the radiant energy, and the energy absorbed by the seed particles is transferred to the gas by conduction and convection.

In addition to having a high absorption coefficient, the seed material must have a low neutron absorption cross section, high melting point, and limited reaction rate with hydrogen. Both heat transfer and neutronic studies of these advanced gaseous uranium reactors require the experimental values of the mass absorption coefficient of different seed materials and their reaction products as a function of wavelength, temperature, and pressure of the aerosol. Also, the reaction rates, reaction product equilibria, and change of state thresholds must be accounted for as a function of temperature and pressure.

The absorption coefficient can best be obtained by measuring the extinction coefficient and the scattering coefficient and calculating the absorption coefficient. Measurement of the extinction coefficient is described in this paper, and other work at Georgia Tech by Williams (Ref. 1) describes the measurement of the scattering coefficient.

Shenoy (Ref. 2) measured the extinction coefficient of hydrogen aerosols with carbon and tungsten seed materials at one atmosphere as a function of temperature and incident radiant energy wavelength. He also measured the extinction coefficient of silicon seed material at room temperature. His measurements exhibited little wavelength dependence but emphasized the importance of the chemical reaction of the aerosol. Carbon especially was found to begin reacting with hydrogen at a much lower temperature than expected. Subsequent measurements by the authors have been made with carbon and silicon seed materials. The methane produced in a carbon aerosol at temperatures up to 3000°F and two atmospheres pressure was observed to be less than one mole percent of the effluent. Interest in carbon seed material continues since it may be desirable to use hydrogen containing a small amount of methane as propellant, to retard the reaction rate of the carbon particles. This research has shown that less than one mole percent of methane greatly retards the reaction rate of carbon and hydrogen (Ref. 3). In addition, the methane may dissociate at a temperature lower than the vaporization temperature of carbon to produce additional carbon particles. It may also be possible to use larger carbon particles which would not completely react before being exhausted from the reactor cavity.

Silicon aerosols produce an extinction coefficient of 65,000 cm²/gm at room temperature and one atmosphere pressure. This is a slight increase over carbon. However, measurements at elevated temperatures and 2 atmospheres pressure have indicated a reaction with hydrogen similar to that observed with carbon. The probable reaction product is SiH₄. Also, silicon scatters much more of the energy than carbon.

Tungsten is a promising seed material due to its very high vaporization point and negligible reaction with hydrogen. Measurements of the extinction coefficient of a 0.2 micron tungsten aerosol at 12 atmospheres and temperatures to 3000°F have been

made (Figures 1-4). There is a slight dependence on temperature. The value of the extinction parameter increases as the temperature increases. This may be due to the thermal agitation of the particle agglomerates and carrier gas causing agglomerate breakup. This is further substantiated by a greater rate of increase in the extinction coefficient at the shorter wavelengths, which is predicted by the Mie theory. The 0.04 micron tungsten data taken at one atmosphere by Shenoy (Ref. 2) exhibit the same behavior trend. More data are required before the effect of pressure can be described. At present the measured values of the extinction coefficient at 12 atmospheres compare favorably with those obtained by Shenoy at one atmosphere.

The current experimental setup at Georgia Tech consists primarily of a 100 atmosphere furnace (Figure 5) capable of temperatures up to 5000°R in which seeded hydrogen is heated and the transmission of a beam of radiant energy is measured as a function of wavelength by a spectrometer. A sampling system is used to measure the density of the aerosol before and after heating. An electrostatic precipitation system is used to collect samples of the particles on electron microscope grids for particle size measurements.

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*Research supported by NASA grant NGR-11-002-068.

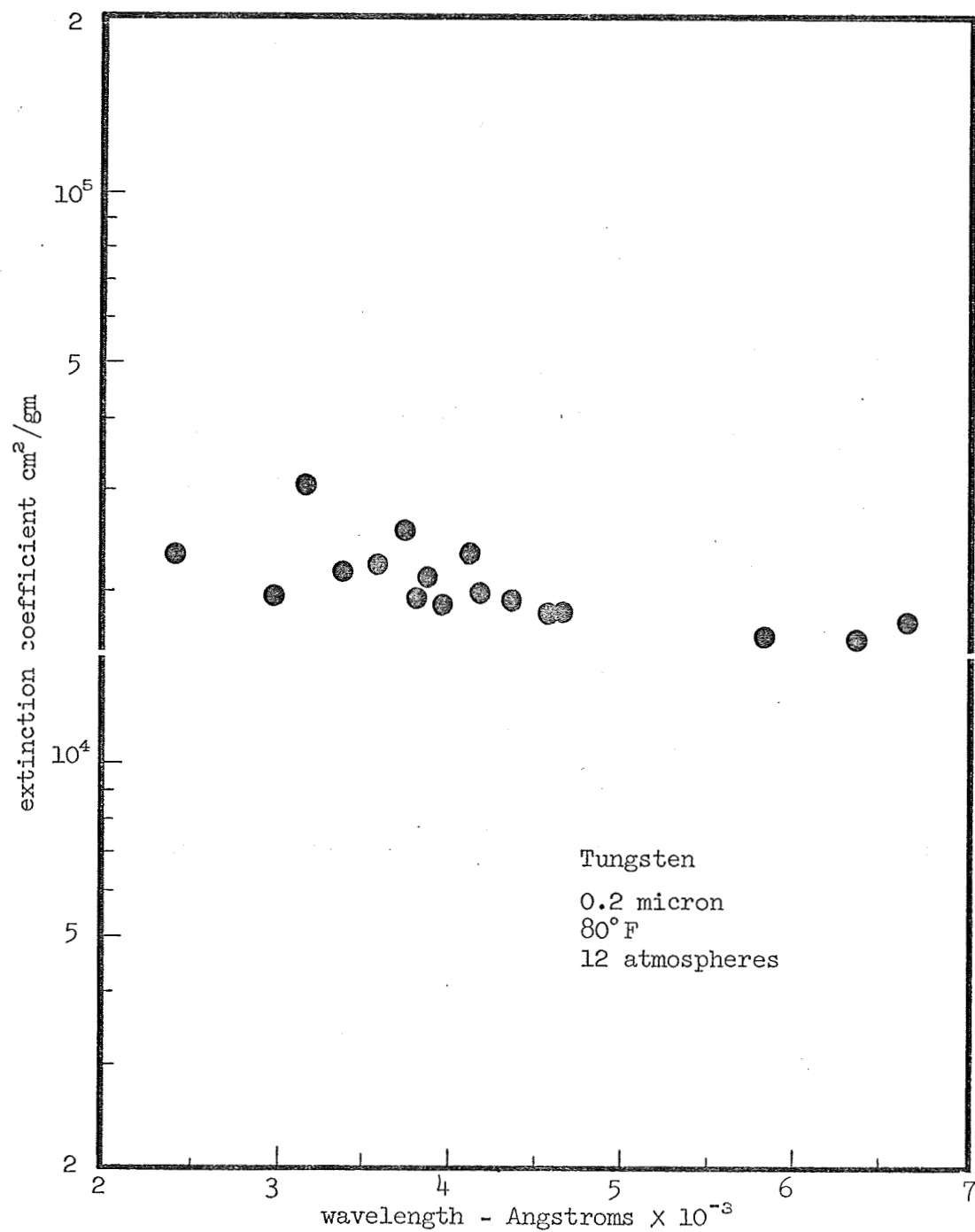


Figure 1. Extinction Coefficient of Tungsten-Hydrogen Aerosol at 80°F and 12 Atmospheres

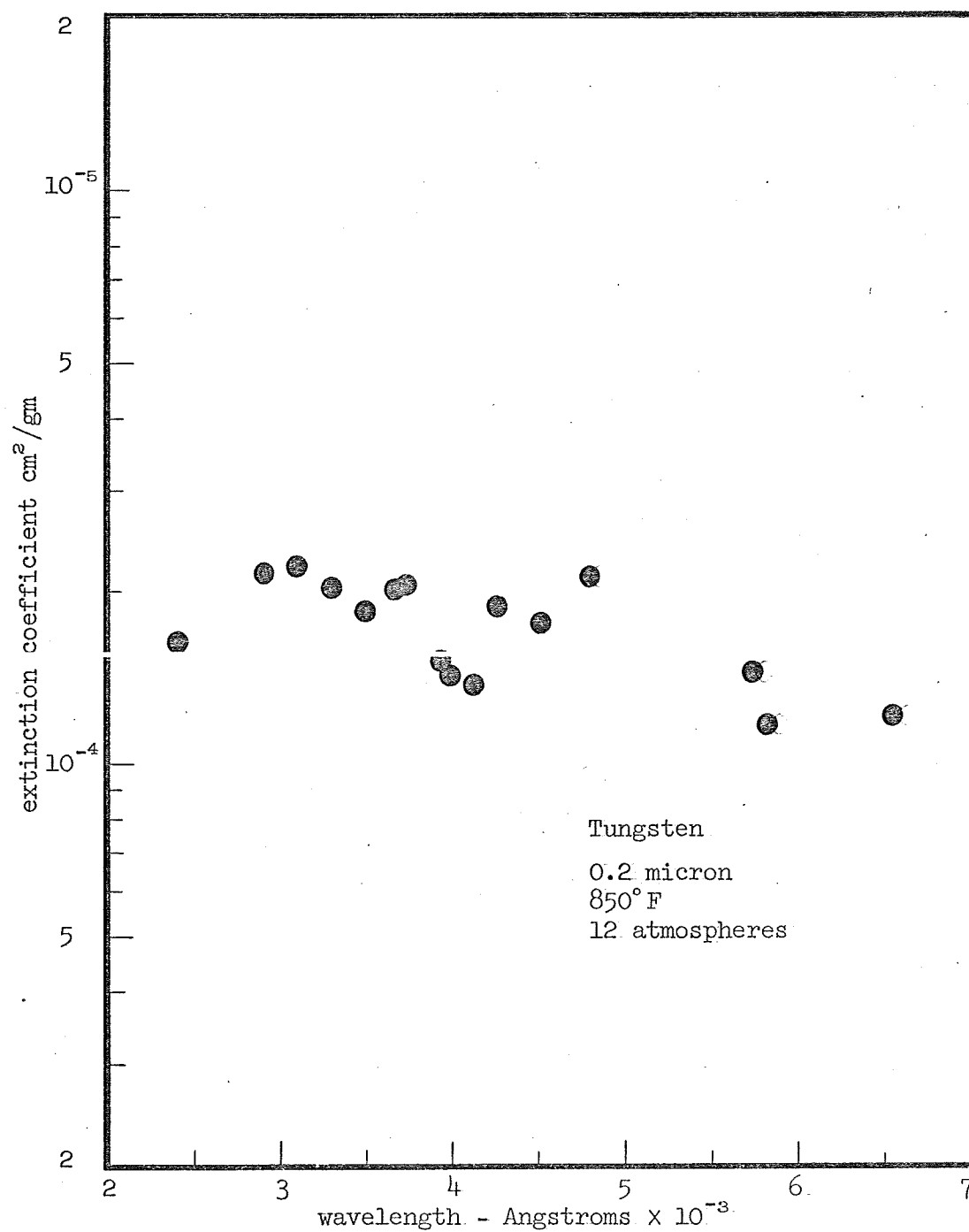


Figure 2. Extinction Coefficient of Tungsten-Hydrogen Aerosol at 850° F and 12 Atmospheres

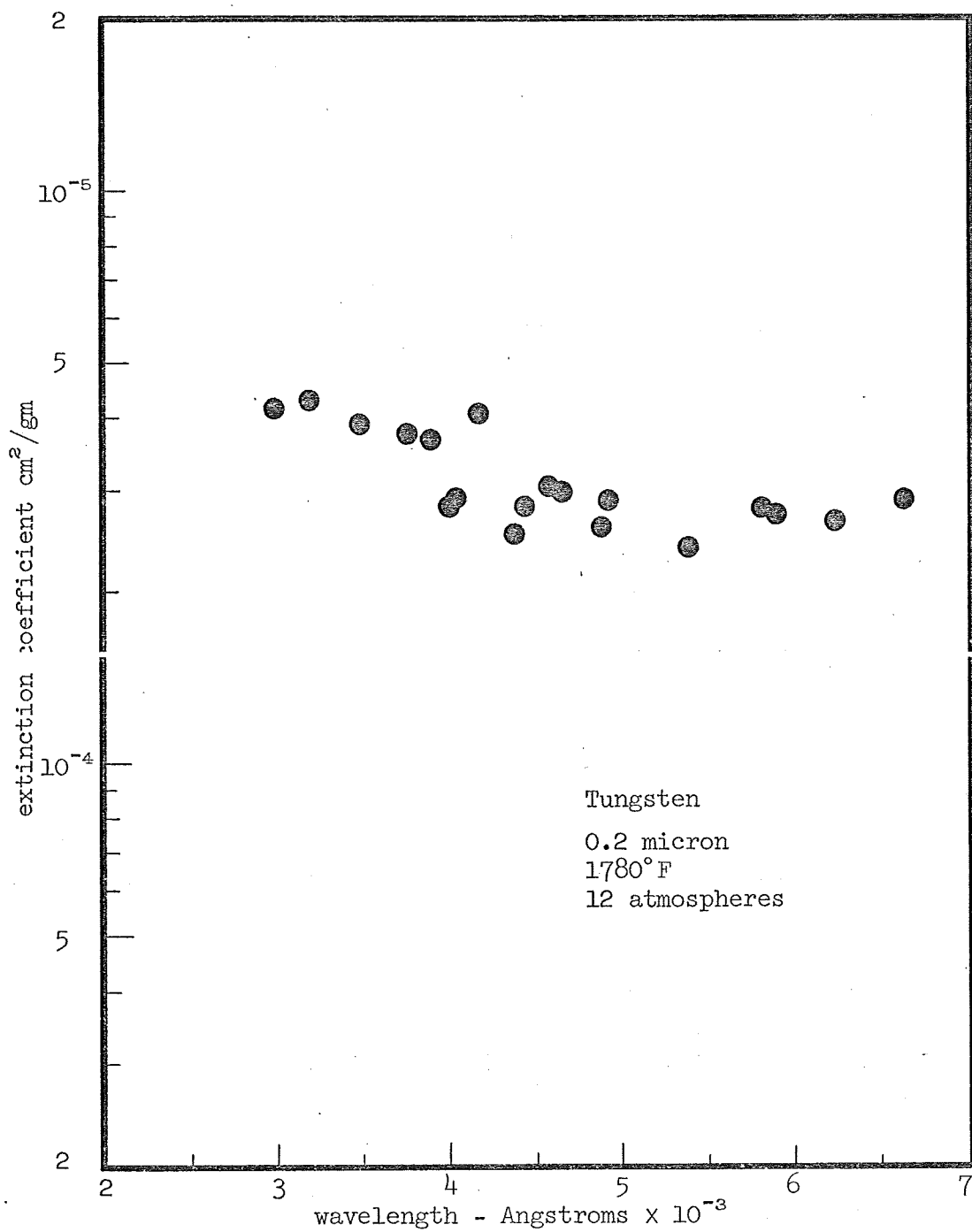


Figure 3. Extinction Coefficient of Tungsten-Hydrogen Aerosol at 1780°F and 12 Atmospheres

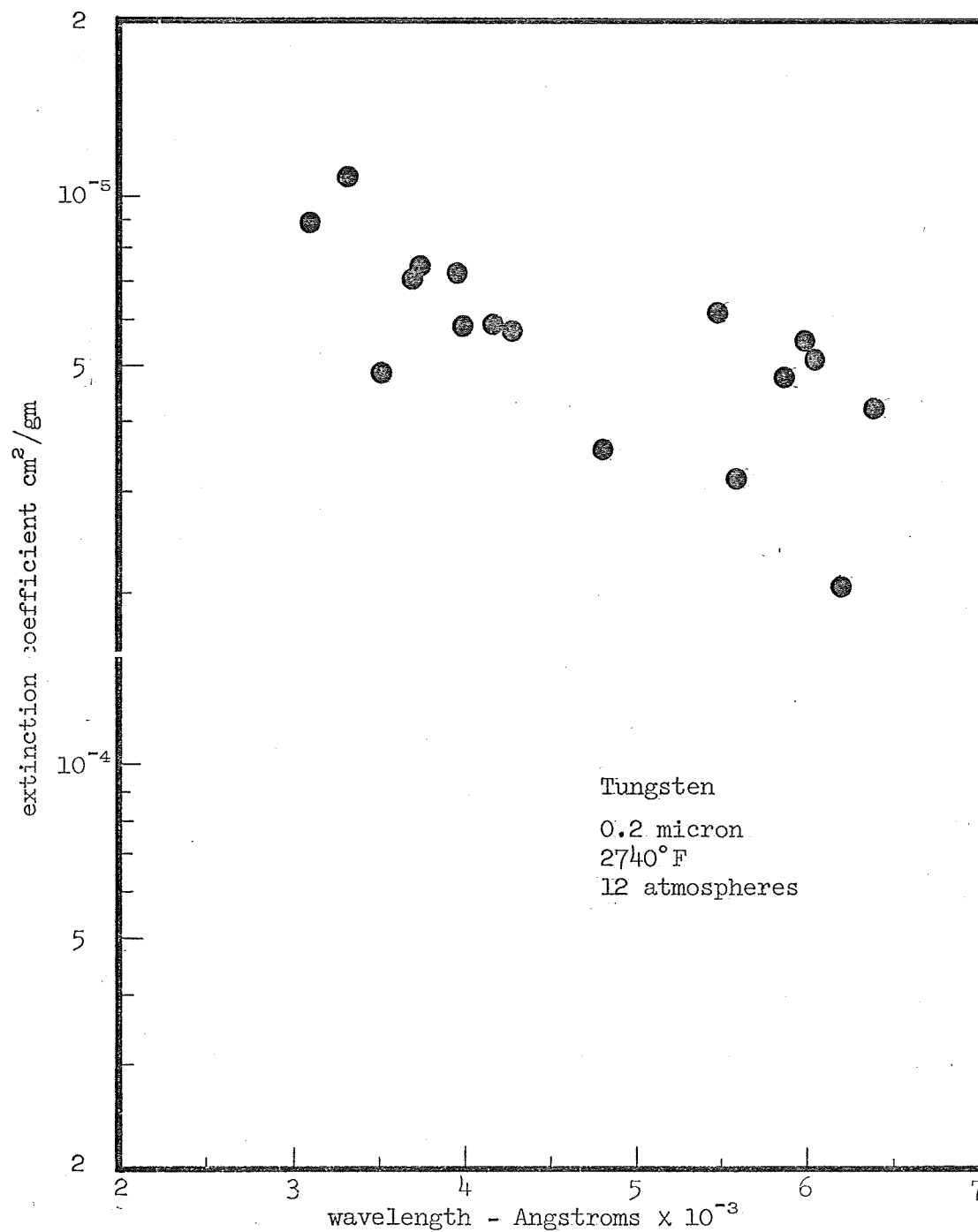


Figure 4. Extinction Coefficient of Tungsten-Hydrogen Aerosol at 2740°F and 12 Atmospheres

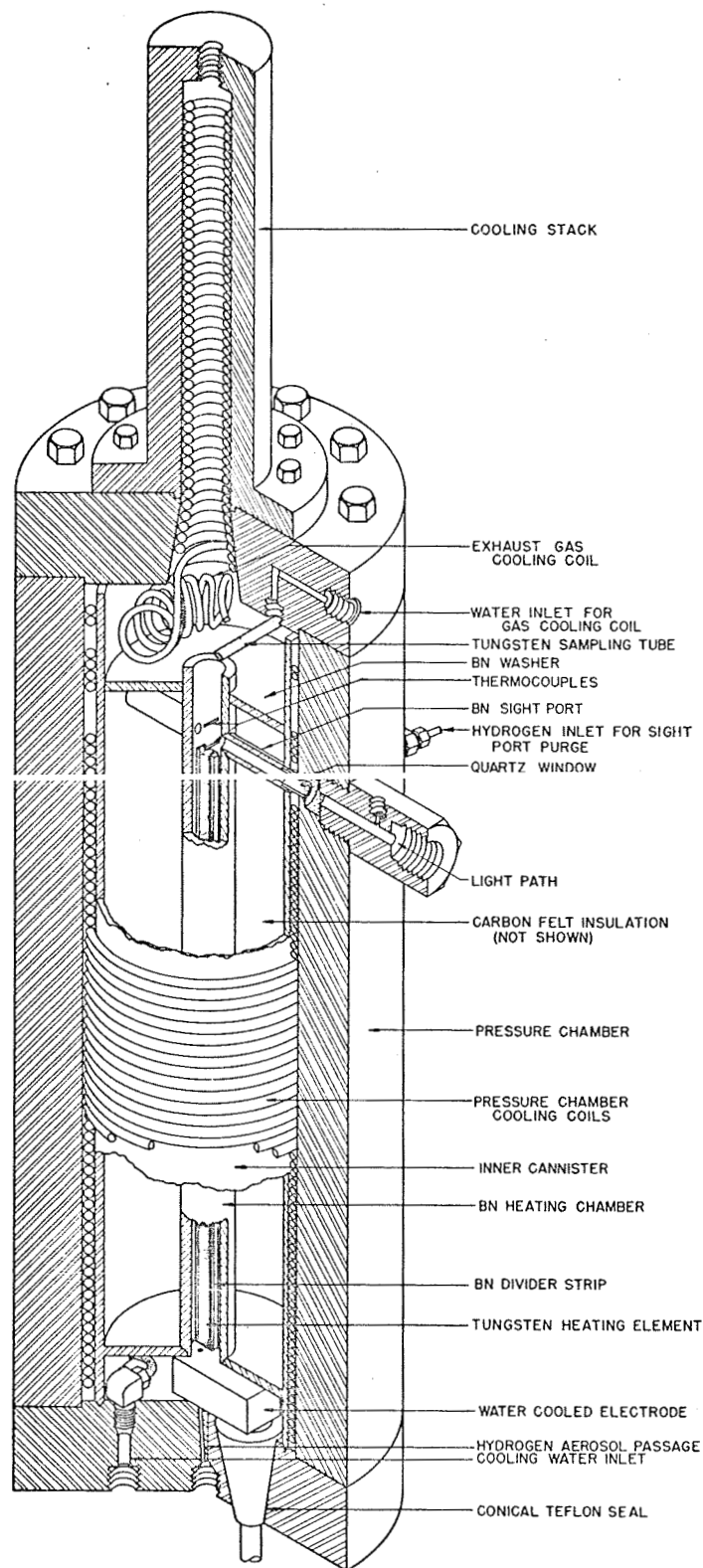


Figure 5. High Pressure Furnace Assembly

4-5 RADIATION TRANSPORT IN A URANIUM PLASMA REACTOR WITH REFLECTING WALLS

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The temperature distribution is determined in the plasma-region of an uranium plasma reactor using the energy equation in which the transport of radiative energy and energy sources are considered. In this case the spatial energy sources correspond to the production of energy per unit volume by nuclear fissions. The anisotropic distribution of the radiation field is included in the calculation of the radiation flux whereas the influence of the plasma flow is neglected.

The results of the calculations show that the temperature can rise up to $22,000^{\circ}\text{K}$ in the middle of the reactor. The total radiation flux near the walls is reduced considerably despite the very high temperatures at the middle of the reactor, because the temperature of the black body radiation near the walls is lower than $7,000^{\circ}\text{K}$. Secondly, the radiation flux is reduced by reflecting walls since liquid lithium flows at the inner walls of the reactor. Liquid lithium reflects more than 90% of the optical radiation from ca. $2,500 \text{ \AA}$ to the far infrared region of the spectrum. Therefore, the optical radiation of the plasma becomes not too high in order to damage the inner walls of the reactor.

At first this plasma reactor can be applied for propulsion systems and secondly for MPD-energy conversion. In the last case of application the plasma reactor is used as a plasma source for an inductive MPD-Converter.

4-6 RADIATION HAZARD FROM FORWARD FLOW OF FISSION FRAGMENTS FROM THE PLUME OF A GAS-CORE NUCLEAR ROCKET

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In the gas-core nuclear rocket concept, the heat source is fissioning uranium gas. This released heat is then absorbed by the hydrogen propellant. In an open cycle gas-core nuclear rocket, fission fragments are formed and exhausted through the nozzle along with the unfissioned fuel and propellant. As the exhaust plume is formed, a small percentage of the plume products have a sufficient velocity and the proper direction to leave the plume and flow forward towards the rocket. It is the purpose of this paper to evaluate the radiation hazard to the crew associated with the forward flow of fission fragments that strike the vehicle. It is assumed the fission fragments that strike the vehicle stick to it.

Typical gas-core engine operating conditions are used as a basis for calculating nozzle exit conditions. The exit gas parameters needed are Mach Number, ratio of specific heat, average molecular weight, average density and average molecular diameter.

The equations of Hill and Draper, (Ref. 1), are used to calculate the plume density as a function of distance from the nozzle. The problem of defining the edge of the plume is then assessed. This is important because inside the plume continuum flow is assumed and outside the plume free molecular flow is assumed. As the molecules reach the plume surface, they leave the plume boundary with a particular direction and velocity and are assumed not to collide with any other molecules thereafter. The definition of the plume boundary was

varied to obtain the largest backflow flux possible under extreme conditions.

Noller, (Ref. 2), has derived the equation for density at a point caused by particles leaving a surface separating continuum and free molecular flow regions. Grier, (Ref. 3), has used this equation to calculate the density forward of a nozzle from the molecules leaving a plume. In this study the equation of Noller, (Ref. 2), had to be reformulated and solved in terms of mass flux instead of density. The basic computer technique of Grier (Ref. 3) was then used to solve the new equation to obtain the flux forward of the nozzle caused by molecules leaving the plume.

In order to calculate the number of fission fragments that strike and stick to the vehicle, a particular shape was picked. The configuration picked was a cylinder 30 feet in diameter and 400 feet long. This size is sufficient for a tankage volume needed to store 600,000 pounds of hydrogen which is typical of a manned Mars mission.

For the total engine running time, 0.95 pounds of fission fragments are ejected out the nozzle with the propellant. About 9.2×10^{-9} pounds flow forward of the nozzle exit plane. Of this amount, 1.4×10^{-10} pounds strike and stick to the vehicle, primarily in the vicinity of the nozzle.

The distribution of fission fragments over the vehicle is computed so that the distance from the fission fragments to the crew is known. The radiation dose from the fission fragments is then computed. Total radiation dose is calculated assuming all the fission fragments release two MEV of energy in decay. This results in over estimating the radiation level. Calculation showed the radiation dose to the crew would be of the order of 2×10^{-3} rad. This radiation level is shown to vary only slightly as a function of reactor power and plume boundary definition.

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4-7 APPLICATIONS OF ZONING TECHNIQUES IN PRACTICAL RADIATIVE ENERGY TRANSPORT PROBLEMS

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Precise analysis of radiative heat transport problems usually can be made only for an ideal black body model and uniform media properties. Zoning techniques are employed to extend the results of these ideal systems to obtain solutions for many complex practical systems with reasonable accuracy and much less effort than the combination of analytical and numerical methods normally used. Applications of zoning techniques to systems of grey surfaces, nonisothermal emitting surfaces, and nonuniform absorption media are discussed. An example for a cylindrical system is given.

5-1 INVESTIGATION OF NUCLEAR LIGHT BULB START-UP AND ENGINE DYNAMICS*

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Analytical studies were conducted to determine the operating conditions of a nuclear light bulb engine during start-up and the transient response of the engine to various perturbations at the nominal full-power operating level. The basic nuclear light bulb engine design was refined, where necessary, to include modifications which resulted from recent criticality studies and test program results.

The start-up study was performed using a simplified analytical model of the basic engine. Three linear power ramps were used and the general engine response, auxiliary power requirements and thermal stress levels were investigated. The calculated responses in temperature and pressure were similar for all of the power ramps. It appears that there will be no major problems with engine control or with excessive thermal stress levels during start-up. Some type of auxiliary power will be required for the turbopump unit during start-up.

Finite-difference approximations to the time-dependent thermal, fluid dynamics and neutron kinetics equations were used to describe the operating characteristics of the engine. These equations were programmed on a UNIVAC 1108 digital computer to construct a dynamic simulation for predicting the response of the engine to selected perturbations occurring at the nominal full-power operating condition. A preliminary transient analysis was performed using the model, which

* This research was supported by the joint AEC-NASA Space Nuclear Propulsion Office under Contracts NASw-847 and SNPC-70.

simulates an uncontrolled engine, to determine the basic stability characteristics and to identify the parameters which would provide the most effective control mechanisms. Responses to perturbations in the uncontrolled system can be characterized by either steady-state or damped oscillations with a characteristic frequency of about 1 cycle/sec. It was concluded that control of the engine could be achieved primarily by control of fuel injection rate.

5-2 CALCULATIONS OF THE SPECTRAL EMISSION FROM THE FUEL REGION OF A NUCLEAR LIGHT BULB REACTOR*

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A theoretical investigation was conducted to determine the spectral emission characteristics of the fuel region of a nuclear light bulb engine and, hence, the spectral radiative flux incident upon the transparent containment walls or upon the reflective end walls of such an engine. The analysis was performed for a specified engine configuration and for a specific nuclear fuel partial pressure distribution. Estimates of the spectral radiative flux emanating from the nuclear fuel region were made for a total radiated flux of 24,300 Btu/ft²-sec (2.757×10^{11} erg/cm²-sec), which corresponds to an effective black-body radiating temperature of 15,000 R (8333 K).

Six cases were considered in order to examine the effects on the spectral radiative flux emitted from the nuclear fuel region of (1) changes in the heavy-atom absorption coefficient model parameters, (2) the addition of a seed gas, and (3) changes in end-wall reflectivities. Three cases involved parametric variations of the heavy-atom model in either the fuel species ionization potentials or in the oscillator strength distribution functions describing line transitions. In the fourth case, the effect of adding hydrogen as a seed gas was studied. The effect of a uniform end-wall spectral reflectivity of 0.5 was examined in the fifth case; similar calculations were made in the sixth case using the spectral reflectivity of aluminum.

* This research was supported by the joint AEC-NASA Space Nuclear Propulsion Office under Contracts NASw-847 and SNPC-70.

5-3 DEVELOPMENT OF A HIGH-INTENSITY R-F RADIANT ENERGY SOURCE FOR SIMULATING THE THERMAL ENVIRONMENT OF THE NUCLEAR LIGHT BULB REACTOR*

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Experiments were conducted to develop an intense radiant energy source capable of producing radiant energy fluxes within the range expected in nuclear light bulb engines. The test program was conducted using the UARL 1.2-megw radio-frequency induction heater at d-c input power levels up to approximately 600 kw. R-F energy was supplied to an argon plasma within a radial-inflow vortex. The effects of several important parameters on the power radiated from the plasma, the power deposited in the surrounding water-cooled transparent peripheral wall, and the power carried away from the vortex by convection were investigated. Tests were conducted at pressures up to 16 atm and with up to 216 kw of power deposited in the steady-state plasma discharge. A maximum of 156 kw was radiated through a 2.24-in. inside diameter water-cooled transparent peripheral wall. The maximum radiant energy flux at the edge of the plasma was 36.7 kw/in.^2 , which corresponds to an equivalent black-body radiating temperature of 10,200 R. The range of edge-of-fuel radiant energy fluxes of interest for full-scale nuclear light bulb engines is from 177.8 kw/in.^2 for a reference engine to 14.4 kw/in.^2 for a derated engine; the corresponding equivalent black-body radiating temperatures are 15,000 R and 8000 R, respectively.

The total power deposited into the plasma, the chamber pressure, and the argon weight flow rate are interrelated in

* This research was supported by the joint AEC-NASA Space Nuclear Propulsion Office under Contracts NASw-847 and SNPC-70.

determining the most stable operating condition for a given geometry. Simultaneous increases in chamber pressure and power into the plasma yielded the largest increases in the fraction of plasma power that was radiated.

5-4 EXPERIMENTS FOR SIMULATING THE ABSORPTION OF THERMAL RADIATION IN THE PROPELLANT DUCT OF A NUCLEAR LIGHT BULB REACTOR*

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Experiments are being conducted to simulate the absorption of thermal radiation in the propellant duct of a nuclear light bulb reactor. The objectives of the experiments are (1) to develop methods for injecting solid particle seeds into a simulated propellant stream, (2) to effectively use buffer layers to prevent coating of the transparent duct walls, and (3) to conduct experiments in which a large percentage of the incident radiation from a high-intensity light source is absorbed in a simulated propellant stream. Argon seeded with micron-sized carbon particles is used as the simulated propellant. Both the UARL 1.2-megw r-f induction heater and the d-c arc heater are used to create high-intensity light sources. Initial low-power-level tests (less than 3 kw radiated) employed configurations in which the seed duct was an annulus formed by two concentric fused silica tubes. The pressure in the seed duct was approximately one atm and the simulated-propellant velocity was about 20 ft/sec. The average temperature rise in the exhaust of the simulated propellant stream was typically 30 R; the maximum temperature rise attained to date is 223 R. The average value of β , the mass attenuation coefficient, was only about 10^3 cm²/gm, and the maximum fraction of the radiation absorbed was 0.33. These initial experiments clearly indicated that increases in

* This research was supported by the joint AEC-NASA Space Nuclear Propulsion Office under Contracts NASw-847 and SNPC-70.

the amount of radiant energy absorbed can be achieved through (1) use of thicker buffer layers between the seeded stream and the duct walls to prevent coating, (2) use of improved deagglomeration techniques to increase the mass attenuation coefficient (a factor of five increase should be attainable), and (3) use of increased radiant energy source power levels.

6-1 ADVANCED NUCLEAR MHD POWER PLANTS

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MHD generators readily handle gas temperatures far greater than those produced even by the solid-core Nerva rocket reactor. With high temperature go the advantages of high power density, high efficiency, and reduced thermal pollution in the case of terrestrial power plants; compact machinery and small heat sink radiators in the case of space power plants. The combination of a gaseous core nuclear reactor with an MHD generator results in a system whose high temperature portion contains no solid parts, either stationary or moving, that are directly involved in the heat generation and conversion process thus paving the way for significant advances over more conventional power systems in terms of simplicity and reliability as well as performance.

This paper will describe some of the systems in which such a combination might be used; describe the present state of development of fossil-fired MHD generators both in this country and abroad; and discuss the relevance of this work to advanced nuclear-MHD applications.

6-2 KINETICS STUDIES OF NUCLEAR SEEDED MHD PLASMAS*

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A new method for studying the electron kinetics in plasmas produced by neutron irradiation of nuclear seeded noble gases is described. Experimentally determined production and loss parameters for plasmas produced by the slowing down of the reaction products of the $^3\text{He}(n,p)t$ reaction is reported for a range of helium gas pressures (1-10 atm) that is of interest for reactor coolant and MHD conversion applications.

The voltage output signal amplitude of the pulsed ionization chamber (PIC) is used to measure the steady-state electron density n_e as a function of reactor power and the measured ionization source rate S (ion pairs/sec) for plasmas produced within the ^3He gas filling of the ion chamber during neutron irradiation in the thermal column of the University of Florida Training Reactor. Plasma loss coefficients can then be determined directly and the mechanisms of production and loss can be studied.

Values reported for the second order plasma loss coefficients obtained with electron densities measured by the PIC technique for steady-state helium plasmas as a function of pressure were in excellent agreement with theoretical predictions and ranged from 5×10^{-8} to 3×10^{-7} (cm^3/s) at 300°K .

*Work supported in part by the U. S. Office of Naval Research

6-3 THE PERFORMANCE OF HELIUM SEEDED WITH URANIUM
IN A MAGNETOHYDRODYNAMIC GENERATOR

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The feasibility of using helium seeded with uranium as a working fluid in a MHD generator is discussed. Non-equilibrium ionization of the seed (uranium), including losses due to electrothermal instabilities, is examined over a range of stagnation temperatures (2000-4000 K), stagnation pressures (10-50 atm), and Mach numbers (0.5-1.5).

The optimum mixture (for maximum power density) of helium and uranium is about six atoms of uranium per thousand atoms of helium. The non-equilibrium conductivity, including the instability losses, is higher than the equilibrium conductivity for the temperature range considered. The output power of a specific generator configuration is presented as a function of stagnation temperature.

The use of a helium uranium mixture appears to be a possibility, although the power density is lower than for more conventional working fluids.

6-4 GAS-CORE REACTORS FOR MHD POWER SYSTEMS

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Among the many new concepts for power generation investigated in the past decade both for space and commercial applications, magnetohydrodynamic (MHD) power generation with gaseous working fluids has received a great deal of attention (Ref. 1). This has been due to its potential for very high efficiencies and power densities coupled with its simplicity of design (Ref. 2). The MHD generator is capable of utilizing very high temperature heat sources, which is necessary to achieve high efficiencies.

The heat sources for MHD generators which have received essentially all the attention have been either combustion devices or solid-core nuclear reactors. The maximum temperatures in combustion devices are approximately 3000°K and are even lower for solid core nuclear reactors. Even when the working fluid is seeded with an easily ionized gas, i.e. cesium or potassium, if the electron temperature is equal to the gas temperature, the electrical conductivity of the fluid is low (Ref. 3-5) particularly after accelerating the gas through a nozzle. This low electrical conductivity was the initial obstacle to actual operation of an MHD device (Ref. 6) and the low conductivity is now the major barrier to the realization of the high efficiencies and power densities of which the MHD generator is theoretically capable (Ref. 3).

A solution to the low electrical conductivity problem was thought to be imminent in the earlier 1960's when non-equilibrium ionization was first investigated for MHD devices.

By heating the electrons to a higher temperature than the gas, the electrical conductivity has been shown to increase by a factor of ten or more. The proposed method of preferentially heating the electrons is by use of the magnetically induced electric field.

This work on nonequilibrium ionization has been directed toward solid-core nuclear reactor heat sources using noble gases, such as argon, in a closed cycle. Nonequilibrium ionization in combustion devices is not feasible because the very large electron-atom and electron-molecule collision cross sections which exist in combustion products make it virtually impossible to obtain a condition of unequal electron and gas temperatures. The energy transfer from the higher temperature electrons to the gas is much too high.

However, even for the solid core nuclear reactor using a closed cycle, Brogan states in Reference 3, "Indeed, almost the total research effort in generator working fluids for use with a nuclear reactor heat source has been given to the single topic of nonequilibrium ionization. It has proven to be an elusive quarry." Magnetically-induced nonequilibrium ionization may still hold the solution to the low electrical conductivity problem, but the most optimistic experimental results so far have failed to produce evidence that the desired values of electrical conductivities (~ 100 mho/cm) can be produced by this method. Brogan (Ref. 3) discusses both basic and practical reasons as to why this attainment of useful nonequilibrium ionization is very difficult.

A heat source capable of higher temperatures than the 2500°K which is available from the solid core nuclear reactor (Ref. 7) is seen then to be very desirable and perhaps even essential. These higher temperatures are available by utilizing the concept of the cavity reactor in which the nuclear fuel is a dust, (Ref. 8), a liquid, (Ref. 9), or a gas. Since the gaseous reactor concept promises higher temperatures and is somewhat simpler than the dust bed or liquid core reactor,

this design has received the most attention.

Three gaseous reactor systems that are currently being investigated are the coaxial flow reactor, (Ref. 10,11) the uranium vortex reactor, (Ref. 12) and the light bulb reactor (Ref. 12-14) (Figure 1). The coaxial flow system utilizes a slow moving central stream of very hot gaseous fissioning fuel to heat a fast moving annular stream of particle-seeded gas by thermal radiation. The vortex concept confines the fissioning fuel in the cavity in a radial inflow vortex. The coaxial flow and vortex concepts are called open cycle systems because the fuel becomes mixed with the working fluid and may have to be separated back out later. The nuclear light bulb reactor, which confines the fissioning gas inside a transparent partition so that the working fluid is heated by thermal radiation through the partition, is a closed cycle concept because the fuel does not become mixed with the working fluid. Since the gas used as a working fluid is not opaque to thermal radiation by itself, it must be seeded with submicron-sized particles to insure maximum heat transfer to the working fluid and minimum heating of the containment vessel and moderator (Ref. 15). The moderator, which surrounds the nuclear fuel and working fluid can be condensed back out when the fluid temperature drops below 3900°K.

The use of a new heat source for MHD generators in the form of a gaseous core nuclear reactor appears to offer two solutions to the low electrical conductivity problem which would remove the major obstacle to achieving the high efficiency and power density of which an MHD generator is potentially capable. The first is the very high working fluid temperature (5000-7000°K) which may be produced with gaseous reactors and the second is the very high radiation flux which is available in the vicinity of such a reactor. This radiation flux may be extremely effective in ionizing the gas and preferentially heating the electrons. It could overcome many of the difficulties which are encountered with magnetically induced nonequilibrium plasmas. The feasibility of increasing

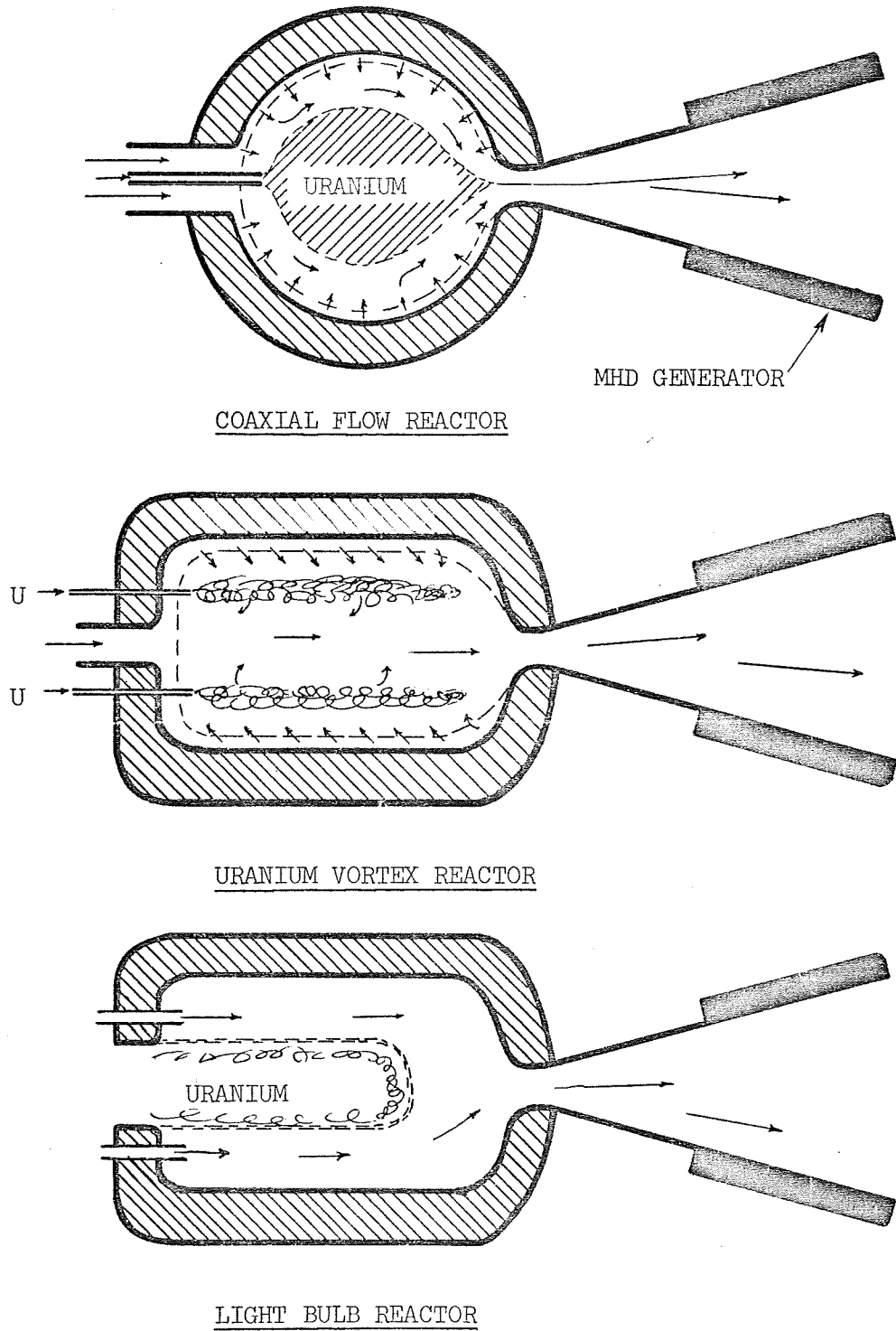


Figure 1. Gas Core Reactor Concepts

the electrical conductivity by different types of radiation has been analyzed in Reference 16 with some encouraging results.

The submicron-sized particles present in the gaseous core reactor could also enhance the electrical conductivity of the fluid by supplying additional electrons by thermionic emission. This phenomenon has in fact been suggested and briefly studied as a possible substitute for potassium or cesium seeding (Ref. 17,18). The combination of solid particle seeding and potassium seeding could be a fruitful approach in MHD generators driven by devices other than a gaseous core nuclear reactor.

The fundamental advantage of combining a MHD generator with a gaseous reactor is a more or less complete removal of any constraint on the top temperature of the thermodynamic cycle. This is particularly important for space power systems which require a high radiator temperature. The gaseous reactor MHD generator may also serve as a topping cycle for large ground based power plants to considerably improve their efficiency. The exhaust from the MHD generator could be used to produce steam for conventional turbines before being returned to the reactor. The problem of thermal pollution has been becoming more acute in recent years and points out the need for more efficient nuclear power plants.

As indicated by Rosa (Ref. 19), the gaseous reactor may very well prevent MHD technology from becoming obsolete. It appears to be the best heat source which is capable of allowing the MHD generator to realize its true inherent advantages.

Various design studies (Ref. 12,20,21) of gaseous reactor systems for nuclear rocket propulsion have been completed. The only significant difference between the nuclear rocket reactor and the gas-core reactor for MHD power would be the use of argon instead of hydrogen as the working fluid. Since the neutron absorption cross section of an argon atom is slightly less than that of a hydrogen molecule the operating characteristics would probably be enhanced by the substitution

of argon for hydrogen. Also the use of argon should improve uranium containment in the open cycle systems.

Table 1 lists some predicted parameters of gaseous reactor MHD space power systems based on reactor designs reported in References 12, 20, and 21. Figure 2 illustrates these plant designs. The open cycle reactor would provide for more efficient generator operation because of the higher temperature of the exhaust, however, the additional operations required to continuously reseparate and recirculate the fuel would probably offset the increased generator efficiency. Thus the net plant efficiency may be about the same for both systems. A plant efficiency of 20 percent for a space power plant is considered by the authors to be conservative.

Large ground based power plants utilizing a gas-core reactor with an MHD topping cycle can be made much more efficient than conventional nuclear power plants (Figure 3). The advantages of the higher efficiency are reduced fuel costs and greatly reduced thermal pollution. Preliminary calculations indicate that thermal efficiencies of 50 to 60 percent are reasonable for such plants. Thus gas-core reactor MHD power plants may serve not only to provide high specific power for nuclear-electric space propulsion but also to greatly alleviate the problem of thermal pollution on the earth.

TABLE 1.
CHARACTERISTICS OF GAS-CORE REACTOR
MHD SPACE POWER SYSTEMS

Reactor Type Cycle	Light Bulb ¹² Closed	Vortex ¹² Open	²⁰ Open	Coaxial ²¹ Open
Reactor Weight (Kg)	32,000	63,000	42,000	96,000
Reactor Power (MW)	4,600	90,000	14,400	25,000
Plant Efficiency	20%	20%	20%	20%
Net Plant Output (MW)	920	18,000	2,880	5,000
Magnetic Coil Weight ²² (Kg)	500	3,000	800	1,000
Radiator Weight (Kg)	4,000	48,000	8,000	14,000
Total System Weight (Kg)	45,000	165,000	68,000	132,000
Specific Power (KW/Kg)	20.4	109	42.4	37.9

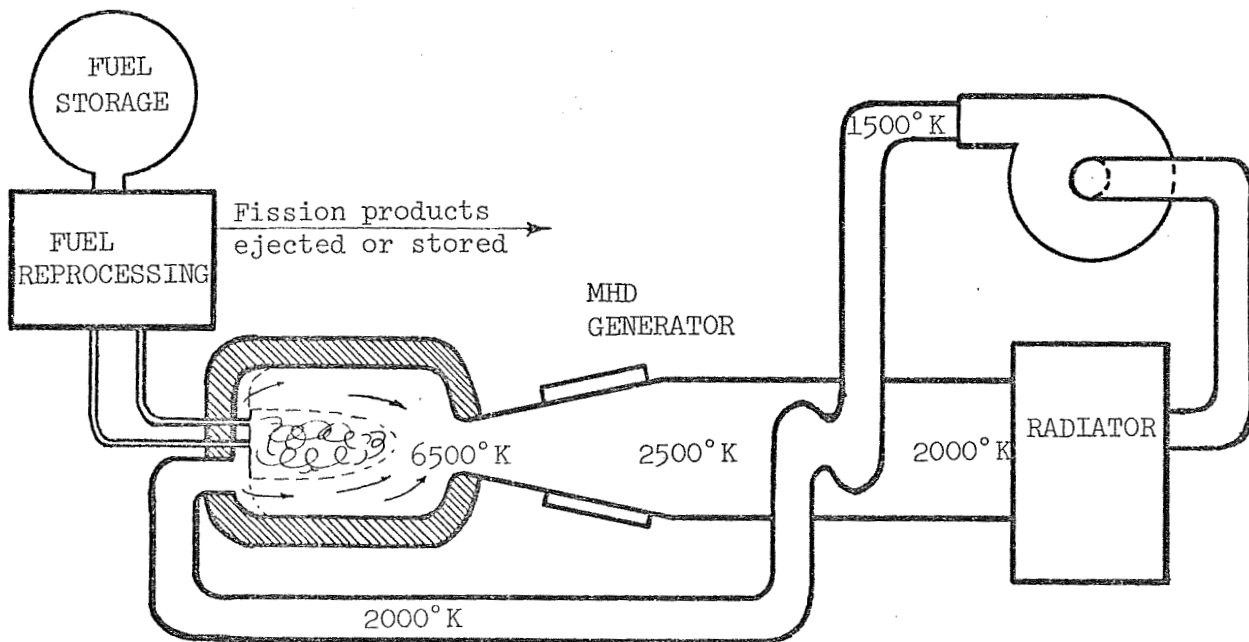
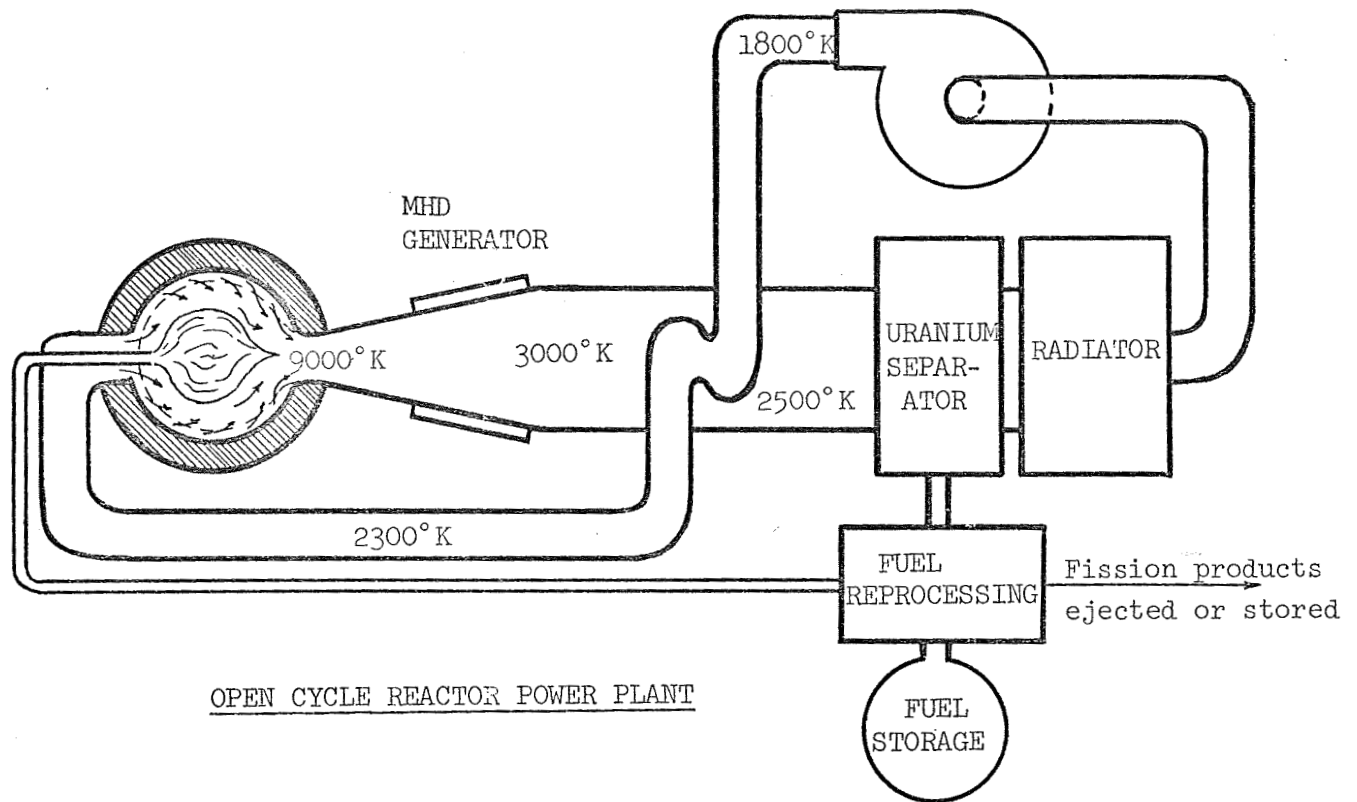


Figure 2. Space Power Plants for Open and Closed Cycle Reactors

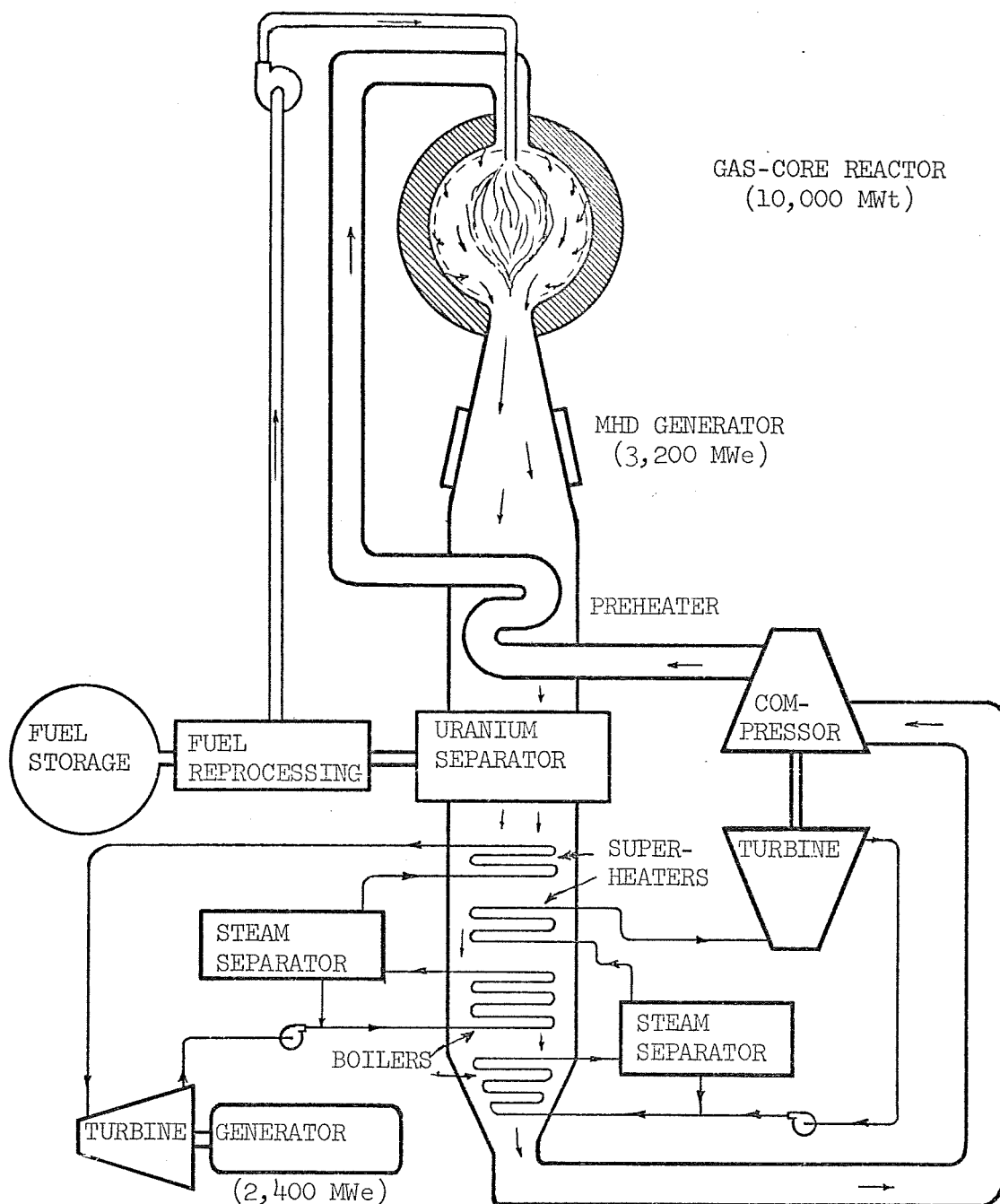


Figure 3. Large Ground Based Power Plant

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7-1 ON GAS LASER PUMPING VIA NUCLEAR RADIATIONS*

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The possibility of producing lasing via a plasma generated by nuclear radiations has been considered by several groups. Earlier feasibility studies by the authors (Ref. 1) are reviewed along with studies by others, including Herwig (Ref. 2), Derr (Ref. 3), DeShong (Ref. 4), and Rusk, et al. (Ref. 5). Theoretical predictions of threshold radiation intensity requirements are reviewed for neutron atom, ionic, and molecular laser systems. Some unique characteristics which may result from nuclear radiation pumping are described.

Convenient radiation sources include nuclear reactors, radioisotopes, and accelerators; but primarily emphasis is given here to plasmas generated by alpha particles or fission fragments released from a boron or uranium coating undergoing neutron irradiation in a nuclear reactor.

The design of and preliminary results from experimental in-core studies of the He-Ne system are presented. These experiments have employed pulsed operation of the University of Illinois TRIGA reactor as well as a fast burst reactor. This work has mainly been concerned with gain-absorption type measurements as a function of gas pressure, but the effect of using additives in the He-Ne system is also discussed.

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7-2 CALCULATIONS OF IONIZATION-EXCITATION RATES IN GASEOUS MEDIA IRRADIATED BY FISSION FRAGMENTS AND ALPHA PARTICLES*

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Experimental data for the slowing of high-energy ions in gaseous and solid media are reviewed with special emphasis on fission fragments and alpha particles. This data is interpreted in terms of a semi-empirical slowing law of the form $T/T_0 = [1 - r/\lambda(T_0)] \frac{1}{n+1}$ where T is the energy of the ion after traveling a distance r , $\lambda(T_0)$ is the range corresponding to the initial energy T_0 , and the parameter n is primarily a function of the type ion involved.

The problem of predicting the spatial distribution of primary ionization-excitation rates in a fluid being irradiated by ions from an adjoining solid fuel layer is considered. The above slowing law is used along with a transmission function method previously developed by the authors (Ref. 1). The method is extended to explicitly include secondary effects due to high-energy secondary electrons (δ -rays) and recoil atoms. Detailed results are presented for the irradiation of helium in a channel bounded by fuel plates on either side.

A survey of the status of data and theory for w -values, ionization, and excitation cross sections for high-energy ions is presented for various gases, with emphasis on helium.

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Preliminary results from spectroscopic studies of a helium plasma created by radiation from a one-curie alpha source is presented. An interpretation in terms of the ionization-excitation rate calculations coupled with appropriate plasma kinetics relations, is proposed.

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7-3 ENHANCEMENT OF LASER OUTPUT BY NUCLEAR REACTIONS

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An experimental investigation is reported of the effect of the $\text{He}^3(n,p)\text{H}^3$ reaction products on the power output of a CO_2 discharge laser. To perform this investigation, a static fill CO_2 laser using mixtures of CO_2 , N_2 , and He was assembled. The laser was capable of producing more than 5 watts of output power using commercial grade He gas. Maximum lasing power was obtained at a total pressure of 10 torr, with a mixture ratio of 1:1:8 of CO_2 , N_2 , and He, respectively. Results are reported on the changes in the operation of the system when research grade He^3 replaced commercial grade He, and the laser was irradiated with thermal neutrons. Reactor facilities at the University of Florida will be used to provide thermal neutron fluxes ranging from 10^5 to 10^{12} neutrons per cm^2 per sec. Results obtained are compared with those reported by Andriahkin, et al. (Ref. 1) in which an attempt at simulating the $\text{He}^3(n,p)\text{H}^3$ reaction was made by irradiating a laser using mixtures of CO_2 , N_2 , and He with a beam of high energy protons (2.8 Mev) obtained from a proton accelerator. A factor of 2 increase in laser power was reported using a 7 μ ampere proton beam. Estimates show that a higher flux of protons should be available from the

$\text{He}^3(n,p)\text{H}^3$ reaction with the neutron fluxes used in our experiment. Comments on the possible effect of the reaction products on the electron temperature and ionization will be made.

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Post Deadline Paper
Session 4

EFFECTS OF COLUMNAR RECOMBINATION ON CONDUCTIVITIES
OF NUCLEAR-SEEDED PLASMAS

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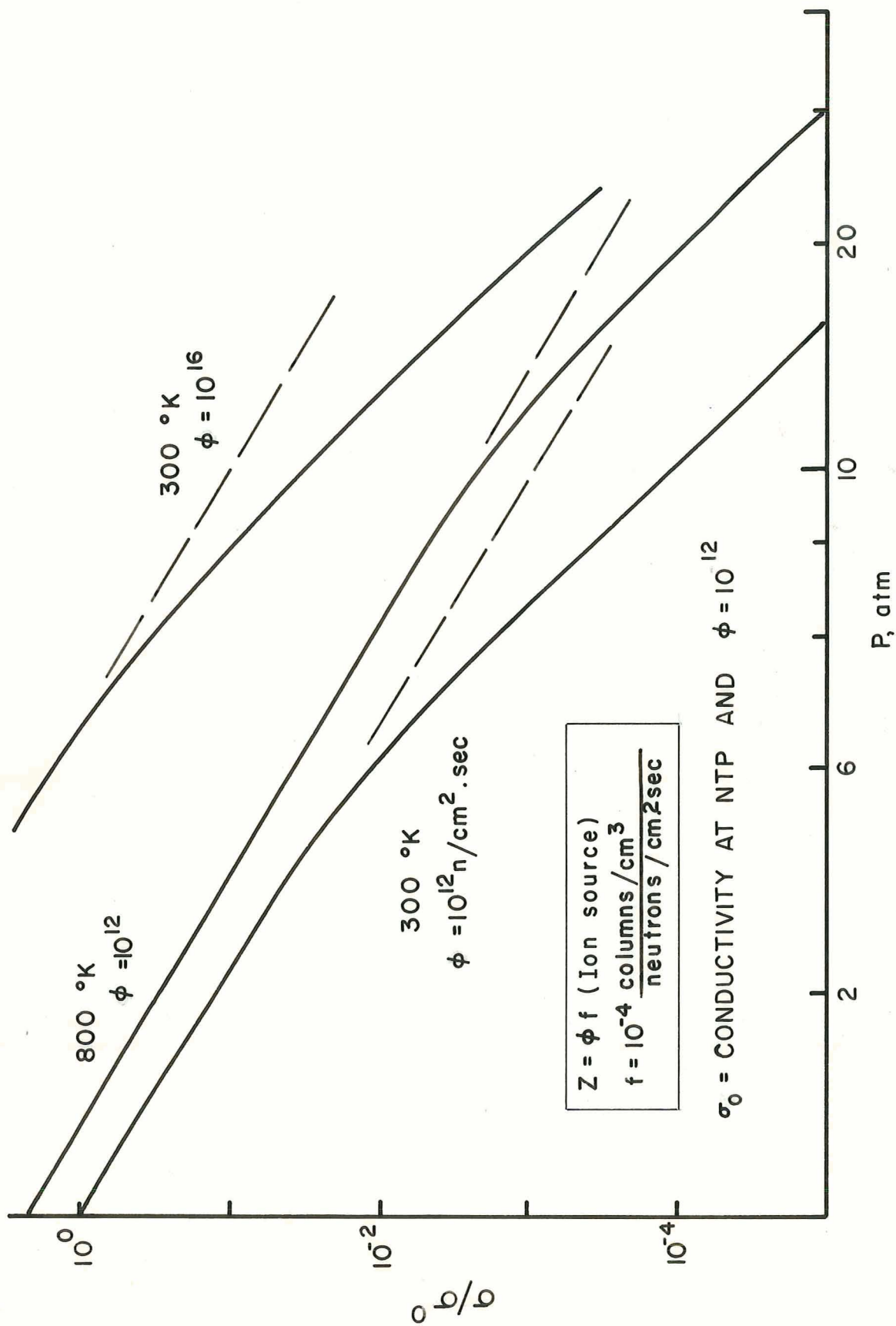
The problems of enhanced recombination and field retarded diffusion have been evaluated in ionization columns used to seed a plasma by nuclear ionization. The time and space dependent diffusion, mobility and recombination differential equations are solved numerically for the cylinder surrounding an initial ionization track.

A wide range of numerical calculations have been made for various temperatures, pressures, recombination coefficients and specific ionizations. Many of these are summarized and evaluated in terms of the fraction of the electrons that diffuse freely versus those that diffuse collectively with the ions and may recombine. It is found that the classical definition of a plasma does indicate the onset of collective motion of ions and electrons. However, one must go to columns a factor of 10 or more higher in density before a significant fraction of the electrons diffuse collectively. Depending upon the recombination coefficient used, the enhancement of recombination due to collective motion begins to be important at higher densities.

In view of the temperatures and pressures likely to be encountered in uranium plasma systems, some calculations have been carried out for temperatures of up to 800°K and 20 atmospheres. These were done for high track ionization densities appropriate to fission fragments in a gas. A series of calculations of conductivity have been carried out taking into

account the effects of recombination and collective (and free) diffusion in helium gas at high temperature and pressures for high specific ionizations. A brief display of these results is given in Fig. 1.

Although the primary objective of this study was the investigation of recombination of proton and triton induced ionization in He gas, some of the results give a good estimate of the effects that may be expected in fission fragment induced ionization. The methods used seem to have ample capacity for extension to more accurate representation of columnar effects in uranium plasmas.



CONDUCTIVITY FOR PSEUDO FISSION FRAGMENT IONIZATION OF HELIUM